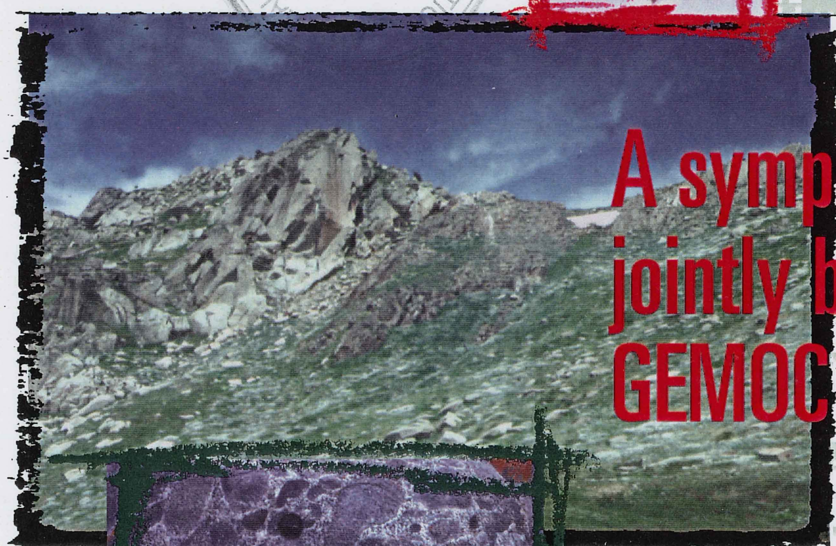
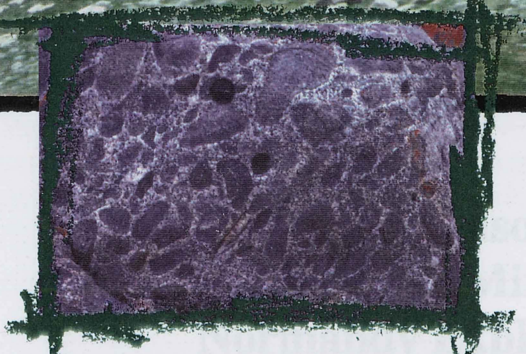
THE BRUCE CHAPPELL SYMPOSIUM

Granites, Island Arcs, the Mantle and Ore Deposits

Record 1998/33





A symposium held jointly between GEMOC and AGSO

Canberra, November 23 and 24th, 1998

ABSTRACT VOLUME

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The Bruce Chappell Symposium:

Granites, Island Arcs, the Mantle and Ore Deposits

A symposium held jointly between GEMOC
(A National Key Centre on the Geochemistry and Metallogeny of the Continents)

and AGSO

(Australian Geological Survey Organisation)

Canberra, November 23 and 24th, 1998

Sponsored by
Newcrest Mining Limited
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ABSTRACT VOLUME

Australian Geological Survey Organisation, Record 1998/33

DEPARTMENT OF INDUSTRY, SCIENCE & RESOURCES

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FOREWARD

Bruce Chappell retired from the Geology Department of the Australian National University on the 6th August 1998. To acknowledge his contribution to geoscience in Australia, some of his former students and colleagues decided to arrange a two-day symposium in his honour on the 23rd and 24th November 1998 in Canberra. The symposium is held in conjunction with GEMOC (Geochemical Evolution and Metallogeny of Continents - an ARC Key Centre between Macquarie University and the Geology Department of the Australian National University), and the Australian Geological Survey Organisation (AGSO).

Bruce has contributed to geoscience in many ways including fundamental research on the geochemistry of granites and research into rapid but accurate analysis of geological materials. He has also been a collaborator on several AMIRA projects investigating the connection between granites and mineralisation and we are very grateful for the sponsorships provided by Newcrest Mining Limited, Normandy Exploration Limited, North Limited and Ross Mining NL, which enabled the program to be expanded to include several overseas speakers.

The program was basically designed to reflect the broad interests of Bruce's career and the majority of the speakers were either colleagues and/or former students. The program was divided into 5 segments, each addressing aspects of work that Bruce has been involved in:

1. Granite magmas,
2. Granites and related igneous rocks and ore deposits
3. Granites through time
4. Island arcs and the mantle
5. Analysis of data and rocks.

As limitations on the size of the venue meant that attendance was restricted to 100 people, this abstract volume is meant to be not just a permanent record of the meeting, in particular for those students and colleagues who regretfully were unable to come, but also to provide an insight into the current state of play in what has now become well known as the 'Chappell and White Granite School'.

Finally, I would like to acknowledge the help of Dell Stafford, Jan Knutson, Liz Webber Saimone Bissett, and Leanne McMahon in helping to organise the Symposium and this volume. Special thanks also to Bev Allen and Anne Franklin for helping to prepare the 'Bruce Chappell Bibliography'.

Lesley Wyborn

AGSO

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ON BRUCE CHAPPELL

Allan J.R. White[1]
[1]VIEPS The University of Melbourne

In 1958 Bruce completed a first class honours degree at the University of New England capping it with the University medal. For his thesis he mapped a Devonian sequence in New England but only got as far as the boundaries of the granite plutons. It was during the following year when employed as a demonstrator at the University of New England that he turned onto the path of his future career. He went from the contacts into the granite themselves.

In 1960 he was appointed lecturer at the fledgling geology department in the University College at Canberra which became part of the National University virtually at that time. Apart from helping Professor David Brown organise the new department he completed an MSc degree part time. The MSc project, on the burial metamorphism and chemical composition of the Permian Baldwin greywackes of New England was a little controversial at the time but is still the only definitive work on composition changes in the first cycle derivation of sediments from andesites.

At last in 1962 the granites attracted his full time research attention. It was at a time when most had read Tuttle and Bowen's 1958 Memoir and almost all had decided that we knew all there was to know about granites and their origin. In spite of a full teaching load, Bruce completed a PhD degree on the Moonbi granites in 1966, mastering and developing along the way the techniques of sampling granites with gelignite, as well as the more delicate methods of chemical analysis by X-ray fluorescence. His detailed work showed that there was a systematic variation in the chemical composition of granite within, and from one pluton to another. The suite concept was developed. He also studied the enclaves in the Moonbi Suite granites and was the first, at least in Australia, to obtain chemical data on these. In his thesis he laid the foundations of the restite model to explain the origin of the granite suites of the Moonbi region, although it was another ten years before this had evolved enough for publication. Also in his thesis work he recognised a suite of granites in New England (Banalaster Suite) which had contrasted markedly with the Moonbi and similar suites of the region. Work on this suite combined with that being done on the Berridale Batholith at that time led to the idea of S- and I-type granites in 1972.

By the late seventies Bruce had embarked on a project to make a geochemical study of every granite in the Lachlan Fold Belt. The data bank of complete analyses for the LFB now exceeds 3000. And the data bank of world class granite analyses is still growing. His research spread to the New England Fold Belt and extends to Far North Queensland. However, just as important as the data acquisition is the applications of his granite studies to our understanding of the crust and crustal processes. The latter is receiving more and more attention since he retired at the beginning of this year. As we shall see in this symposium given in his honour, he is still coming up with new models to explain granites forty years after Tuttle and Bowen's definitive work.

Bruce's career culminated in 1998 when he was elected Fellow of the Australian Academy of Science on the 30th of April, 1998.

BIBLIOGRAPHY OF BRUCE CHAPPELL

PUBLICATIONS

1. Chappell, B W, 1961. The stratigraphy and structural geology of the Manilla-Moore Creek district, N.S.W. *Journal and Proceedings of the Royal Society of New South Wales* **95**, 63-75.

2. Heier, K S, Chappell, B W, Arriens, P A, and Morgan, J W, 1966. The geochemistry of four Icelandic basalts. *Norsk Geologisk Tidsskrift* **46**, 427-437.

3. Norrish, K, and Chappell, B W, 1967. X-ray fluorescence spectrography. In: Zussman, J (ed.), *Physical Methods in Determinative Mineralogy*, pp. 161-214. Academic Press, London.

4. Chappell, B W, 1968. Volcanic greywackes from the Upper Devonian Baldwin Formation, Tamworth-Barraba district, New South Wales. *Journal of the Geological Society of Australia* **15**, 87-102.

5. Chappell, B W, and White, A J R, 1968. The X-ray spectrographic determination of sulfur coordination in scapolite. *American Mineralogist* **53**, 735-1738.

6. Banno, S, and Chappell, B W, 1969. X-ray fluorescent analysis of Rb, Sr, Y, Pb and Th in Japanese Paleozoic slates. *Geochemical Journal* 3, 127-134.

7. Chappell, B W, 1969. Granitic intrusions from the southern end of the New England Batholith. *Journal of the Geological Society of Australia* **16**, 278-282.

8. Chappell, B W, Compston, W, Arriens, P A, and Vernon, M J, 1969. Rubidium and strontium determinations by X-ray fluorescence spectrometry and isotope dilution below the part per million level. *Geochimica et Cosmochimica Acta* **33**, 1002-1006.

9. Compston, W, Chappell, B W, Arriens, P A, and Vernon, M J, 1969. On the feasibility of NBS 70a K-feldspar as a Rb-Sr age reference sample. *Geochimica et Cosmochimica Acta* **33**, 753-757.

10. Chappell, B W, and White, A J R, 1970. Further data on an 'eclogite' from the Sittampundi Complex, India. *Mineralogical Magazine* **37**, 555-560.

11. Compston, W, Arriens, P A, Vernon, M J, and Chappell, B W, 1970. Rubidium-strontium chronology and chemistry of lunar material. *Science* **167**, 474-476.

12. Compston, W, Chappell, B W, Arriens, P A, and Vernon, M J, 1970. The chemistry and age of Apollo 11 lunar material. In: Proceedings of the Apollo 11th Lunar Science Conference, Houston, Texas, 1970, Chemical and Isotope Analysis. *Geochimica et Cosmochimica Acta Supplement,* Volume 2, 1007-1027, Pergamon.

13. Compston, W, Berry, H, Vernon, M J, Chappell, B W, and Kay, M J, 1971. Rubidium-strontium chronology and chemistry of lunar material from the Ocean of Storms. In: Proceedings of the 2nd Lunar Science Conference, *Geochimica et Cosmochimica Acta Supplement* 2, **2**, 1471- 1485.The MIT Press.

14. Lovering, J F, Le Maitre, R W, and Chappell, B W, 1971. Murchison C2 carbonaceous chondrite and its inorganic composition. *Nature, Physical Science* **230**, 1, 18-20.

15. Chappell, B W, Compston, W, Green, D H, and Ware, N G, 1972. Chemistry, Geochronology, and Petrogenesis of Lunar Sample 15555. *Science* **175**, 415-416.

16. Compston, W, Vernon, M J, Berry, H, Rudowski, R, Gray, C M, Ware, N, Chappell, B W, and Kay, M J, 1972. Age and petrogenesis of Apollo 14 basalts. In: *Lunar Science, III*. LSI Contribution, 88, 151-153. Lunar Science Institute, Houston, United States.

17. Compston, W, Vernon, M J, Berry, H, Rudowski, R, Gray, C M, Ware, N, Chappell, B W, and Kay, M J, 1972. Apollo 14 mineral ages and the thermal history of the Fra Mauro Formation. In: Proceedings of the 3rd Lunar Science Conference, *Geochimica et Cosmochimica Acta Supplement* 3, **2**, 1487-1501.

18. Mackenzie, D E, and Chappell, B W, 1972. Shoshonitic and calc-alkaline lavas from the Highlands of Papua New Guinea. *Contributions to Mineralogy and Petrology* **35**, 50-62.

19. White, A J R, Chappell, B W, and Jakes, P, 1972. Coexisting clinopyroxene, garnet and amphibole from an "eclogite", Kakanui, New Zealand. *Contributions to Mineralogy and Petrology* **34**, 185-191.

20. Chappell, B W, and Green, D H, 1973. Chemical compositions and petrogenetic relationships in Apollo 15 mare basalts. *Earth and Planetary Science Letters* **18**, 237-246.

21. Compston, W, Vernon, M J, Chappell, B W, and Freeman, R S, 1973. Rb-Sr model ages and chemical composition of nine Apollo 16 soils. *Lunar Science IV*, pp. 158-158b. Lunar Science Institite, Houston, Texas.

22. Chappell, B W, and White, A J R, 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

23. White, A J R, Chappell, B W, and Cleary, J R, 1974. Geologic setting and emplacement of some Australian Paleozoic batholiths and implications for intrusive mechanisms. *Pacific Geology* **8**, 159-171.

24. Price, R C, and Chappell, B W, 1975. Fractional crystallisation and the petrology of Dunedin Volcano. *Contributions to Mineralogy and Petrology* **53**, 157-182.

25. Williams, I S, Compston, W, Chappell, B W, and Freeman, R S, 1975. Rubidium-strontium age determinations on micas from a geologically controlled, composite batholith. *Journal of the Geological Society of Australia* **22**, 497-505.

26. Chappell, B W, and White, A J R, 1976. Plutonic rocks of the Lachlan Mobile Zone. *25th International Geological Congress, Sydney, 1976, Field Guide,* 13C, 40 pp.

27. White, A J R, Williams, I S, and Chappell, B W, 1976. *Berridale 1:100 000 Geological Sheet.* New South Wales Geological Survey, Sydney.

28. White, A J R, Williams, I S, and Chappell, B W, 1976. The Jindabyne Thrust and its tectonic, physiographic and petrogenetic significance. *Journal of the Geological Society of Australia* **23**, 105-112.

29. Flood, R H, Vernon, R H, Shaw, S E, and Chappell, B W, 1977. Origin of pyroxene-plagioclase aggregates in rhyodacite. *Contributions to Mineralogy and Petrology* **60**, 229-309.

30. Frey, F A, Ferguson, J, and Chappell, B W, 1977. Petrogenesis of South African and Australian kimberlitic suites. *2nd International Kimberlite Conference* 1977, Santa Fe, October 3-7, 1977, 3 pp.

31. Norrish, K, and Chappell, B W, 1977. X-ray fluorescence spectrometry. In Zussman, J (ed.), *Physical Methods in Determinative Mineralogy,* 2nd Edition, pp. 201-272. Academic Press, London.

32. O'Neil, J R, and Chappell, B W, 1977. Oxygen and hydrogen isotope relations in the Berridale batholith. *Journal of the Geological Society of London*, **133**, 559-571.

33. Smith, I E M, Chappell, B W, Ward, G K, and Freeman, R S, 1977. Peralkaline rhyolites associated with andesitic arcs of the southwest Pacific. *Earth and Planetary Science Letters* **37**, 230-236.

34. White, A J R, and Chappell, B W, 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

35. White, A J R, Williams, I S, and Chappell, B W, 1977. *Geology of the Berridale 1:100 000 sheet 8625.* Geological Survey of New South Wales, Sydney, 138 pp.

36. Bultitude, R J, Johnson, R W, and Chappell, B W, 1978. Andesites of Bagana volcano, Papua New Guinea: chemical stratigraphy, and a reference andesite composition. *BMR Journal of Australian Geology and Geophysics* **3**, 281-295.

37. Chappell, B W, 1978. Granitoids from the Moonbi District, New England Batholith, eastern Australia. *Journal of the Geological Society of Australia* **25**, 267-283.

38. Eggleton, R A, and Chappell, B W, 1978. The crystal structure of stilpnomelane. Part 3: chemistry and physical properties. *Mineralogical Magazine* **42**, 361-368.

39. Frey, F A, Chappell, B W, and Roy, S D, 1978. Fractionation of rare-earth elements in the Tuolumne Intrusive Series, Sierra Nevada Batholith, California. *Geology* **6**, 239-242.

40. Griffin, T J, White, A J R, and Chappell, B W, 1978. The Moruya Batholith and geochemical contrasts between the Moruya and Jindabyne suites. *Journal of the Geological Society of Australia* **25**, 235-247.

41. Hine, R, Williams, I S, Chappell, B W, and White A J R, 1978. Contrasts between I- and S- type granitoids of the Kosciusko Batholith. *Journal of the Geological Society of Australia* **25**, 219-234.

42. Jaques, A L, Chappell, B W, and Taylor, S R, 1978. Geochemistry of LIL-element enriched tholeiites from the Marum Ophiolite Complex, northern Papua New Guinea. *BMR Journal of Australian Geology and Geophysics* **3**, 297-310.

43. Bateman, P C, and Chappell, B W, 1979. Crystallization, fractionation, and solidification of the Tuolumne Intrusive Series, Yosemite National Park, California. *Geological Society of America, Bulletin,* Part 1, **90**, 465-482.

44. Compston, W, and Chappell, B W, 1979. Sr-isotope evolution of granitoid source rocks. In: McElhinny, M W, (ed.), *The Earth: Its Origin, Structure and Evolution*, pp. 377-126, Academic Press, London.

45. Johnson, R W, and Chappell, B W, 1979. Chemical analyses of rocks from the late Cainozoic volcanoes of north-central New Britain and the Witu Islands, Papua New Guinea. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report* **209** (MF 76).

46. Silver, L T, Taylor, H P, and Chappell, B W, 1979. Some petrological, geochemical and geochronological observations of the Peninsular Ranges Batholith near the international border of the U.S.A. and Mexico. In: Abbott, P L and Todd, V R (eds), *Geological Society of America 1979 Guidebook*, pp. 83-110.

47. Ferguson, J, Chappell, B W, and Goleby, A B, 1980. Granitoids in the Pine Creek Geosyncline. Uranium in the Pine Creek Geosyncline: In: Ferguson, J, and Goleby, A B, (eds), *Proceedings of the International Symposium on the Pine Creek Geosyncline,* pp. 73-90. International Atomic Energy Agency, Vienna.

48. Flood, R H, Shaw, S E, and Chappell, B W, 1980. Mineralogical and chemical matching of plutonic and associated volcanic units, New England Batholith, Australia. *Chemical Geology* **29**, 163-170.

49. Gust, D A, Johnson, R W, and Chappell, B W, 1980. Petrological data catalogue for Boisa Island, an andesitic volcano in Papua New Guinea: whole-rock, mineral, and modal analyses and modelling data. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report* **227** (MF 147).

50. Jaques, A L, and Chappell, B W, 1980. Petrology and trace element geochemistry of the Papuan Ultramafic Belt. *Contributions to Mineralogy and Petrology* **75**, 55-70.

51. Wyborn, D, Chappell, B W, and Johnston, R M, 1981. Three S-Type volcanic suites from the Lachlan Fold Belt, southeast Australia. *Journal of Geophysical Research* **86**(B11), 10335-10348.

52. Collins, W J, Beams, S D, White, A J R, and Chappell, B W, 1982. Nature and origin of A-type granites with particular reference to southeastern Australia. *Contributions to Mineralogy and Petrology* **80**, 189-200.

53. Hensel, H D, Chappell, B W, Compston, W, and McCulloch, M T, 1982. A neodymium and strontium isotopic investigation of granitoids and possible source rocks from New England, eastern Australia. In: Flood, P G, and Runnegar, B, (eds), *New England Geology.* Proceedings of a Symposium on the Geology of the New England Region, Armidale, July, 1982, pp. 193-200. University of New England, Armidale, NSW.

54. McCulloch, M T, and Chappell, B W, 1982. Nd isotopic characteristics of S- and I-type granites. *Earth and Planetary Science Letters* **58**, 51-64.

55. McCulloch, M T, Arculus, R J, Chappell, B W, and Ferguson, J, 1982. Isotopic and geochemical studies of nodules in kimberlite have implications for the lower continental crust. *Nature* **300**, 166-169.

56. Arculus, R J, Johnson, R W, Chappell, B W, McKee, C O, and Sakai, H, 1983. Ophiolite-contaminated andesites, trachybasalts, and cognate inclusions of Mount Lamington, Papua New Guinea: anhydrite-amphibole-bearing lavas and the 1951 cumulodome. *Journal of Volcanology and Geothermal Research* **18**, 215-247.

57. Jaques, A L, Chappell, B W, and Taylor, S R, 1983. Geochemistry of cumulus peridotites and gabbros from the Marum Ophiolite Complex, northern Papua New Guinea. *Contributions to Mineralogy and Petrology* **82**, 154-164.

58. Johnson, R W, Macnab, R P, Arculus, R J, Ryburn, R J, Cooke, R J S, and Chappell, B W, 1983. Bamus volcano, Papua New Guinea: dormant neighbour of Ulawun, and magnesian-andesite locality. *Geologische Rundschau* **72**, 207-237.

59. Wallace, D A, Johnson, R W, Chappell, B W, Arculus, R J, Perfit M R, and Crick, I H, 1983. Cainozoic volcanism of the Tabar, Lihir, Tanga, and Feni Islands, Papua New Guinea: geology, whole-rock analyses, and rock-forming mineral compositions. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report* **243** (MF 197).

60. White, A J R, and Chappell, B W, 1983. Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia. In: Roddick, J A, (ed.), *Circum-Pacific Plutonic Terranes*, Geological Society of America, Memoir **159**, 21-34.

61. Williams, I S, Compston, W, and Chappell, B W, 1983. Zircon and monazite U-Pb systems and the histories of I-type magmas, Berridale Batholith, Australia. *Journal of Petrology* **24**, 76-97.

62. Wyborn, L A I, and Chappell, B W, 1983. Chemistry of the Ordovician and Silurian greywackes of the Snowy Mountains, southeastern Australia: an example of chemical evolution of sediments with time. *Chemical Geology* **39**, 81-92.

63. Bowden, P, Batchelor, R A, Chappell, B W, Didier, J, and Lameyre, J, 1984. Petrological, geochemical and source criteria for the classification of granitic rocks: a discussion. *Physics of the Earth and Planetary Interiors* **35**, 1-11.

64. Chappell, B W, 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *Philosophical Transactions of the Royal Society of London, Series A*, **310**, 693-707.

65. Chappell, B W, and White, A J R, 1984. I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. In: Keqin, X, and Guangchi, T, (eds) *Geology of Granites and their Metallogenetic Relations. Proceedings of the International Symposium held at Nanjing University, Nanjing, China, October 26-30, 1982*, pp. 87-101. China Science Press, Beijing.

66. Jaques, A L, Lewis, J D, Smith, C B, Gregory, G P, Ferguson, J, Chappell, B W, and McCulloch, M T, 1984. The diamond-bearing ultrapotassic (lamproitic) rocks of the West Kimberley region, Western Australia. In: Kornprobst, J, (ed.), *Proceedings of the Third International Kimberlite Conference, Clermont Ferrand, September, 1982, Vol.1: Kimberlites and Related Rocks.* Developments in Petrology 11A, pp. 225-254. Elsevier, Amsterdam.

67. Sawka, W N, Chappell, B W, and Norrish, K, 1984. Light-rare-earth-element zoning in sphene and allanite during granitoid fractionation. *Geology* **12**, 131-134.

68. Silver, L T, Woodhead, J A, Williams, I S, and Chappell, B W, 1984. Uranium in granites from the Southwestern United States: actinide parent-daughter systems, sites and mobilization, second year report. Report for the United States Department of Energy, 1984, GJBX-7(84).

69. White, A J R, Collins, W J, and Chappell, B W, 1984. Influence of melt structure on the trace element composition of granites. In: Keqin, X, and Guangchi, T (eds), *Geology of Granites and their Metallogenetic Relations. Proceedings of the International Symposium held at Nanjing University, Nanjing, China, October 26-30, 1982*, pp. 737-751. China Science Press, Beijing.

70. Windrim, D P, McCulloch, M T, Chappell, B W, and Cameron, W E, 1984. Nd isotopic systematics and chemistry of central Australian sapphirine granulites: an example of rare earth element mobility. *Earth and Planetary Science Letters* **70**, 27-39.

71. Ewart, A, Chappell, B W, and Le Maitre R W, 1985. Aspects of the mineralogy and chemistry of the intermediate-silicic Cainozoic volcanic rocks of eastern Australia. Part 1: introduction and geochemistry. *Australian Journal of Earth Sciences* **32**, 359-382.

72. Glikson, M, Chappell, B W, Freeman, R S, and Webber, E, 1985. Trace elements in oil shales, their source and organic association with particular reference to Australian deposits. *Chemical Geology* **53**, 155-174

73. Hensel, H D, McCulloch, M T, and Chappell, B W, 1985. The New England Batholith: constraints on its derivation from Nd and Sr isotopic studies of granitoids and country rocks. *Geochimica et Cosmochimica Acta* **49**, 369-384.

74. Hill, R I, Silver, L T, Chappell, B W, and Taylor, H P, 1985. Solidification and recharge of SiO_2-rich plutonic magma chambers. *Nature* **313**, 643-646.

75. Johnson, R W, Jaques, A L, Hickey, R L, Gregory, G P, Ferguson, J, Chappell, B W, and McCulloch, M T, 1985. Manam Island, Papua New Guinea: petrology and geochemistry of a low-TiO_2 basaltic island-arc volcano. *Journal of Petrology* **26**, 283-323.

76. Sawka, W N, and Chappell, B W, 1985. Geothermal implications for the Sierra Nevada Batholith from vertical and horizontal compositional zoning studies in contrasting pluton types. In: *High Heat Production (HHP) Granites, Hydrothermal Circulation and Ore Genesis. Papers Presented at the Conference, Organized by the Institution of Mining and Metallurgy, St. Austell, Cornwall, England, 22-25 September, 1985*, pp. 329-343. Institution of Mining and Metallurgy, London

77. Both, R, Crook, K, Taylor, B, Brogan, S, Chappell, B W, Frankel, E, Liu L, Sinton, J, and Tiffin, D, 1986. Hydrothermal chimneys and associated fauna in the Manus back-arc basin, Papua New Guinea. *Eos, Transactions, American Geophysical Union* **67**, 489-490.

78. Dickson, W L, White, A J R, Clemens, J D, Holloway, J R, Silver, L T, Chappell, B W, and Wall, V J, 1986. S-type granites and their probable absence in southwestern North America; discussion and reply. *Geology* **14**, 894-895.

79. Glikson, M, Chappell, B W, Freeman, R S, and Webber, E, 1986. Why environmental effects from mining and retorting of Rundle (Qld) oil shale may be minimal. Proceedings of the Third Australian Workshop on Oil Shale, Lucas Heights, 15-16 May, 1986. Sutherland, NSW: CSIRO. Division of Energy Chemistry, pp. 277-282.

80. Kistler, R W, Chappell, B W, Peck, D L, and Bateman, P C, 1986. Isotopic variation in the Tuolumne intrusive suite, central Sierra Nevada, California. *Contributions to Mineralogy and Petrology* **94**, 205-220.

81. Miller, C F, White, A J R, Clemens, J D, Holloway, J R, Silver, L T, Chappell, B W, and Wall, V J, 1986. S-type granites and their probable absence in southwestern North America; discussion and reply. *Geology* **14**, 804-806.

82. Sawka, W N, and Chappell, B W, 1986. The distribution of radioactive heat production in I- and S-type granites and residual source regions: implications to high heat flow areas in the Lachlan Fold Belt, Australia. *Australian Journal of Earth Sciences* **33**, 107-118.

83. Sawka, W N, Banfield, J F, and Chappell, B W, 1986. A weathering-related origin of widespread monazite in S-type granites. *Geochimica et Cosmochimica Acta* **50**, 171-175.

84. White, A J R, Clemens, J D, Holloway, J R, Silver, L T, Chappell, B W, and Wall, V J, 1986. S-type granites and their probable absence in southwestern North America. *Geology* **14**, 115-118.

85. Wyborn, D, and Chappell, B W, 1986. The petrogenetic significance of chemically related plutonic and volcanic rock units. *Geological Magazine* **123**, 618-627.

86. Arndt, N T, Brugmann, G E, Lehnert, K, Chauvel, C, and Chappell, 1987. Geochemistry, petrogenesis and tectonic environment of Circum-Superior Belt basalts, Canada. In: Pharaoh, T C, Beckinsale, R D, and Rickard, D (eds), *Geochemistry and Mineralization of Proterozoic Volcanic Suites, Geological Society. Special Publication,* 33, pp. 133-145. Blackwell Scientific Publications, Oxford.

87. Borg, S G, Stump, E, Chappell, B W, McCulloch, M T, Wyborn, D, Armstrong, RL, and Holloway, J R, 1987. Granitoids of northern Victoria Land, Antarctica: implications of chemical and isotopic variations of regional crustal structure and tectonics. *American Journal of Science* **287**, 127-169.

88. Chappell, B W, White, A J R, and Wyborn, D, 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* **28**, 1111-1138.

89. Glikson, M, Chappell, B W, and Webber, E, 1987. Trace element associations in raw and spent oil shales from the Rundle oil shale complex in Queensland; environmental implications. *Fuel* **66**, 400-403.

90. Johnson, R W, Jaques, A L, Langmuir, C H, Perfit, M R, Staudigel, H, Dunkley, P N, Chappell, B W, Taylor S R, and Baekisapa, M, 1987. Ridge subduction and forearc volcanism; petrology and geochemistry of rocks dredged from the western Solomon Arc and Woodlark Basin. In: Marine Geology, Geophysics and Geochemistry of the Woodlark Basin-Solomon Islands. *Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series* **7**, 155-226.

91. Kay, M J, and Chappell, B W, 1987. X-ray fluorescence spectrometric analysis of the Allende Meteorite reference sample. In: The Allende Meteorite Reference Sample. *Smithsonian Contributions to the Earth Sciences* **27**, 28-29.

92. Perfit, M R, Langmuir, C H, Baekisapa, M, Chappell, B W, Johnson, R W, Staudigel, H, and Taylor, S R, 1987. Geochemistry and petrology of volcanic rocks from the Woodlark Basin; addressing questions of ridge subduction. In: Marine Geology, Geophysics and Geochemistry of the Woodlark Basin-Solomon Islands. *Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series* **7**, 113-154.

93. Sawka, W N, and Chappell, B W, 1987. Mafic xenoliths from I- and S-type granitoids; evidence for variations in deep crustal radioactive heat production. In: Heat Production in the Continental Lithosphere. *Geophysical Research Letters* **14**, 303-306.

94. Stephenson, P J, and Chappell, B W, 1987. A major north-west dyke swarm zone in north Queensland. Pacific Rim Congress 87. Proceedings of an International Congress on the Geology, Structure, Mineralisation and Economics of the Pacific Rim, 26-29 August, 1987, Gold Coast, Queensland, Australia, pp. 817-822.. Australasian Institute of Mining and Metallurgy, Parkville, Victoria.

95. Whalen, J B, Currie, K L, and Chappell, B W, 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* **95**, 407-419.

96. Wyborn, D, Turner, B S, and Chappell, B W, 1987. The Boggy Plain Supersuite: a distinctive belt of I-type igneous rocks of potential economic significance in the Lachlan Fold Belt. *Australian Journal of Earth Sciences* **34**, 21-43.

97. Anderson, R N, Dove, R E, Broglia, C, Silver, L T, James, E W, and Chappell, B W, 1988. Elemental and mineralogical analyses using geochemical logs from the Cajon Pass scientific drillhole, California, and their preliminary comparison with core analyses. In: Cajon Pass Scientific Drilling Project. *Geophysical Research Letters* **15**, 969-972.

98. Arculus, R J, Ferguson, J, Chappell, B W, Smith, D, McCulloch, M T, Jackson, I, Hensel, H D, Taylor, S R, Knutson, J, and Gust, D A, 1988. Trace element and isotopic characteristics of eclogites and other xenoliths derived from the lower continental crust of southeastern Australia and southwestern Colorado Plateau, USA. In: Smith, D C (ed.) Eclogites and Eclogite-Facies Rocks, pp. 335-386. Elsevier, Amsterdam.

99. Bateman, P C, Chappell, B W, Kistler, R W, Peck, D L, Busacca, A J, 1988. Tuolumne Meadows Quadrangle, California; analytic data. *U. S. Geological Survey Bulletin*, **1819**.

100. Chappell, B W, and Stephens, W E, 1988. Origin of infracrustal (I-type) granite magmas. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **79**, 71-86.

101. Chappell, B W, White, A J R, and Hine, R, 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **35**, 505-521.

102. Ewart, A, Chappell, B W, and Menzies, M A, 1988. An overview of the geochemical and isotopic characteristics of the eastern Australia Cainozoic volcanic province. In: Menzies, M A, and Cox, K G (eds), Oceanic and Continental Lithosphere; Similarities and Differences. *Journal of Petrology Special Lithosphere Issue*, 1988; pp. 225-273.

103. Hill, R I, Chappell, B W, and Silver, L T, 1988. San Jacinto Intrusive Complex: 2. Geochemistry. *Journal of Geophysical Research* **93**, 10,349-10,372.

104. Johnson, R W, Perfit, M R, Chappell, B W, Jaques, A L, Shuster, R D, and Ridley, W I, 1988. Volcanism in the New Ireland Basin and Manus Island region: notes on the geochemistry and petrology of some dredged volcanic rocks from a rifted-arc region. Circum-Pacific Council for Energy and Mineral Resources. *Earth Science Series* **9**, 113-130.

105. Nelson, D R, Chivas, A R, Chappell, B W, and McCulloch, M T, 1988. Geochemical and isotopic systematics in carbonatites and implications for the evolution of ocean-island sources. *Geochimica et Cosmochimica Acta* **52**, 1-17.

106. Sawka, W N, and Chappell, B W, 1988. Fractionation of uranium, thorium and rare earth elements in a vertically zoned granodiorite: implications for heat production distributions in the Sierra Nevada batholith, California, U.S.A. *Geochimica et Cosmochimica Acta* **52**, 1131-1143.

107. Silver, L T, and Chappell, B W, 1988. The Peninsular Ranges Batholith: an insight into the evolution of the Cordilleran batholiths of southwestern North America. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **79**, 105-121.

108. Silver, L T, James, E W, and Chappell, B W, 1988. Petrological and geochemical investigations at the Cajon Pass deep drillhole. In: Cajon Pass Scientific Drilling Project. *Geophysical Research Letters* **15**, 961-964.

109. Smith, I E M, White, A J R, Chappell, B W, and Eggleton, R A, 1988. Fractionation in a zoned monzonite pluton: Mount Dromedary, southeastern Australia. *Geological Magazine* **125**, 273-284.

110. Whalen, J B, and Chappell, B W, 1988. Opaque mineralogy and mafic mineral chemistry of I- and S-type granites of the Lachlan Fold Belt, southeast Australia. *American Mineralogist* **73**, 281-296.

111. White, A J R, and Chappell, B W, 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **79**, 169-181

112. White, A J R, and Chappell, B W, 1988. Granites. In: Douglas, J G, and Ferguson, J A, (eds) *Geology of Victoria*, pp. 427-439. Geological Society of Australia Victorian Division, Melbourne.

113. Arculus, R J, Ferguson, J, Chappell, B W, Smith, D, McCulloch, M T, Jackson, I, Hensel, H D, Taylor, S R, Knutson, J. and Gust, D.A, 1989. Eclogites and granulites in the lower continental crust: examples from eastern Australia and southwestern U.S.A. In: Smith, D C (ed.), *Eclogites and Eclogite-Facies Rocks*, pp. 335-386. Elsevier, Amsterdam.

114. Chappell, B W, and Hergt, J M, 1989. The use of known Fe content as a flux monitor in neutron activation analysis. *Chemical Geology* **78**, 151-158.

115. Ewart, A, Chappell, B W, and Menzies, M A, 1989. East Australian petrology and geochemistry. In: Johnson, R W, Knutson, J, and Taylor, S R, (eds), *Intraplate Volcanism in Eastern Australia and New Zealand*, pp. 189-248. Australian Academy of Science and Cambridge University Press, Sydney.

116. Hergt, J M, Chappell, B W, Faure, G, and Mensing, T M, 1989. The geochemistry of Jurassic dolerites from Portal Peak, Antarctica. *Contributions to Mineralogy and Petrology* **102**, 298-305.

117. Hergt, J M, Chappell, B W, McCulloch, M T, McDougall, I, and Chivas, A R, 1989. Geochemical and isotopic constraints on the origin of the Jurassic dolerites of Tasmania. *Journal of Petrology* **30**, 841-883.

118. Jaques, A L, Kerr, I D, Lucas, H, Sun, S -S, and Chappell, B W, 1989. Mineralogy and petrology of picritic monchiquites from Wandagee, Carnarvon Basin, Western Australia. *Kimberlites and Related Rocks. Volume 1. Their Composition, Occurrence, Origin and Emplacement.* Proceedings of the Fourth International Kimberlite Conference, Perth, Western Australia 11-15 August, 1986. Geological Society of Australia Special Publication **14**, 120-139

119. Jaques, A L, Sun, S -S, and Chappell, B W, 1989. Geochemistry of the Argyle (AK1) lamproite pipe, Western Australia. *Kimberlites and Related Rocks. Volume 1. Their Composition, Occurrence, Origin and Emplacement.* Proceedings of the Fourth International Kimberlite Conference, Perth, Western Australia, 11-15 August, 1986. *Geological Society of Australia, Special Publication* **14**, 170-188.

120. White, A J R, and Chappell, B W, 1989. *Geology of the Numbla 1:100 000 Sheet (8624).* New South Wales Geological Survey, Sydney.

121. White, A J R, Chappell, B W, Williams, I S, and Glen, R A, 1989. *Numbla 1:100 000 Geological Sheet.* New South Wales Geological Survey, Sydney.

122. Chappell, B W, White, A J R, and Williams, I S, 1990. ICOG 7. Seventh International Conference on Geochronology, Cosmochronology and Isotope Geology, Excursion guide B-1. Cooma Granodiorite and Berridale Batholith, 16 September, 1990. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1990/50**, 53 pp.

123. Chappell, B W, Williams, I S, White, A J R, and McCulloch, M T, 1990. ICOG 7. Seventh International Conference on Geochronology, Cosmochronology and Isotope Geology, Excursion Guide A-2. Granites of the Lachlan Fold Belt, 18-22 September, 1990. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1990/48**, 95 pp.

124. Chen, Y D, Price, R C, White, A J R, and Chappell, B W, 1990. Mafic inclusions from the Glenbog and Blue Gum granite suites, southeastern Australia. *Journal of Geophysical Research* **95(B11)**, 17,757-17,785.

125. Jaques, A L, O'Neill, H St C, Smith, C B, Moon, J, and Chappell, B W, 1990. Diamondiferous peridotite xenoliths from the Argyle (AK1) lamproite pipe, Western Australia. *Contributions to Mineralogy and Petrology* **104**, 255-276.

126. Richards, J P, Chappell, B W, and McCulloch, M T, 1990. Intraplate-type magmatism in a continent-island-arc collision zone: Porgera intrusive complex, Papua New Guinea. *Geology* **18**, 958-961.

127. Sawka, W N, Chappell, B W, and Kistler, R W, 1990. Granitoid compositional zoning by side-wall boundary layer differentiation: evidence from the Palisade Crest intrusive suite, central Sierra Nevada, California: *Journal of Petrology* **31**, 519-553.

128. Sawka, W N, Heizler, M T, Kistler, R W, and Chappell, B W, 1990. Geochemistry of highly fractionated I- and S-type granites from the tin-tungsten province of western Tasmania. *In* Stein, H.J. and Hannah, J.L. (eds), *Ore-bearing systems; Petrogenesis and Mineralizing Processes, Geological Society of America, Special Paper* **246**, 161-179.

129. White, A J R, and Chappell, B W, 1990. Per migma ad magma downunder. *Geological Journal*, **25**, 221-225.

130. Chappell, B W, 1991. Trace element analysis of rocks by X-ray spectrometry. *Advances in X-Ray Analysis* **34**, 263-276.

131. Chappell, B W, and White, A J R, 1991. Restite enclaves and the restite model. In: Didier, J, and Barbarin, B (eds), *Enclaves and Granite Petrology*, pp. 375-381. Elsevier, Amsterdam.

132. Chappell, B W, English, P M, King, P L, White, A J R, and Wyborn, D, 1991. Granites and related rocks of the Lachlan Fold Belt (1:1 250 000 scale map), *Bureau of Mineral Resources, Geology and Geophysics, Australia.*

133. Chappell, B W, White, A J R, and Williams, I S, 1991. Second Hutton Symposium on Granites and Related Rocks, Canberra, September, 1991. Excursion guide: a transverse section through granites of the Lachlan Fold Belt. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/22**, 125 pp.

134. Chen, Y, Chappell, B W, and White, A J R, 1991. Mafic enclaves of some I-type granites of the Palaeozoic Lachlan Fold Belt, south eastern Australia. In: Didier, J, and Barbarin, B (eds), *Enclaves and Granite Petrology*, pp. 113-124. Elsevier, Amsterdam.

135. Richards, J P, Chappell, B W, McCulloch, M T, and McDougall, I, 1991. The Porgera gold deposit, Papua New Guinea, 1: association with alkalic magmatism in a continent-island-arc collision zone. In: E.A. Ladeira E A, (ed.) Brazil Gold '91: the *Economics, Geology, Geochemistry and Genesis of Gold Deposits.* Proceedings of the Symposium, Belo Horizonte, 13-17 May, 1991. Rotterdam: A.A. Balkema, pp. 307-312.

136. Richards, J P, McCulloch, M T, Chappell, B W, and Kerrich, R, 1991. Sources of metals in the Porgera gold deposit, Papua New Guinea: evidence from alteration, isotope, and noble metal geochemistry. *Geochimica et Cosmochimica Acta* **55**, 565-580.

137. White, A J R, Chappell, B W, and Wyborn, D, 1991. Enclaves of S-type granites in the Lachlan Fold Belt, southeastern Australia. In: Didier, J, and Barbarin, B (eds), *Enclaves and Granite Petrology*, pp. 493-507. Elsevier, Amsterdam.

138. Wyborn, D, White, A J R, and Chappell, B W, 1991. Enclaves in the S-type Cowra Granodiorite. Second Hutton Symposium on Granites and Related Rocks, Canberra, 1991. Excursion guide, 25. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/24**, 33 pp.

139. Blevin, P L, and Chappell, B W, 1992. The role of magma sources, oxidation states and fractionation in determining the granite metallogeny of eastern Australia. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 305-316.

140. Champion, D C, and Chappell, B W, 1992. Petrogenesis of felsic I-type granites: an example from northern Queensland. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 115-126.

141. Chappell, B W, and White, A J R, 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 1-26.

142. Ewart, A, Schon, R W, and Chappell, B W, 1992. The Cretaceous volcanic-plutonic province of the central Queensland (Australia) coast - a rift related 'calc-alkaline' province. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 327-345.

143. Hill, R I, Campbell, I H, and Chappell, B W, 1992. Crustal growth, crustal reworking, and granite genesis in the southeastern Yilgarn Block, Western Australia. In: Glover, J E and Ho, S E (eds), *The Archaean: Terrains, Processes and Metallogeny, Proceedings Volume for the Third International Archaean Symposium, Perth, Western Australia*, 17-21 September, 1990. University of Western Australia. Department of Geology, University Extension, Publication, 22, pp. 203-212

144. Hill, R I, Chappell, B W, and Campbell, I H, 1992. Late Archaean granites of the southeastern Yilgarn Block, Western Australia: age, geochemistry, and origin. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 211-226.

145. Johnston, C, and Chappell, B W, 1992. Topaz-bearing rocks from Mount Gibson, north Queensland, Australia. *American Mineralogist* **77**, 303-313.

146. Pratson, E L, Anderson, R N, Dove, R E, Lyle, M, Silver, L T, James, E W, and Chappell, B W, 1992. Geochemical logging in the Cajon Pass drill hole and its application to a new, oxide, igneous rock classification scheme. *Journal of Geophysical Research* **97(B4)**, 5167-5180.

147. Allen, C M, and Chappell, B W, 1993. Contrasting Carboniferous-Permian and Cretaceous plutonism in the Urannah Batholith, northern New England Fold Belt. *New England Orogen*, Eastern Australia. University of New England, Department of Geology and Geophysics, pp. 573-579.

148. Blevin, P L, and Chappell, B W, 1993. The influence of fractionation and magma redox on the distribution of mineralisation associated with the New England Batholith. *New England Orogen*, Eastern Australia. University of New England, Department of Geology and Geophysics, pp. 423-429.

149. Chappell, B W, White, A J R, and Wyborn, D, 1993. The Cowra Granodiorite and its enclaves. IAVCEI Canberra 1993: excursion guide, September, 1993. *Australian Geological Survey Organisation, Record* **1993/67**, 17 pp.

150. Rudnick, R L, McDonough, W F, and Chappell, B W, 1993. Carbonatite metasomatism in the northern Tanzanian mantle: petrographic and geochemical characteristics. *Earth and Planetary Science Letters* **114**, 463-475.

151. Allen, C M, Chappell, B W, Wooden, J L, and Williams, I S, 1994. Ages, compositions, and sources of the Urannah Batholith. In: Henderson, R A, and Davis, B K, (eds), *New developments in geology and metallogeny: northern Tasman Orogenic Zone*. James Cook University of North Queensland,Economic Geology Research Unit. Contributions **50**, 107-110.

152. Chappell, B W, 1994. Lachlan and New England: fold belts of contrasting magmatic and tectonic development (47th Clarke Memorial Lecture). *Journal and Proceedings of the Royal Society of New South Wales* **127**, 47-59.

153. Chappell, B W, and Champion, D C, 1994. Determination of felsic granite types and its application to north Queensland. In: Henderson, R A, and Davis, B K, (eds), *New developments in geology and metallogeny: northern Tasman Orogenic Zone*. James Cook University of North Queensland, Economic Geology Research Unit. Contributions **50**, 141-145.

154. Ewart, A, Bryan, W B, Chappell, B W, and Rudnick, R L, 1994. Regional geochemistry of the Lau-Tonga arc and backarc systems. In: Hawkins, J, Parson, L, and Allan, J, *et al.*, (eds), *Proceedings of the ODP Scientific Results,* **135**, 385-425. Ocean Drilling Program, College Station, Texas.

155. Blevin, P L, and Chappell, B W, 1995. Chemistry, origin and evolution of mineralized granites in the Lachlan Fold Belt, Australia: the metallogeny of I- and S- type granites. *Economic Geology* **90**, 1604-1619.

156. Johnson, R W, McKee, C O, Eggins, S, Woodhead, J, Arculus, R J, Chappell, B W, and Sheraton, J, 1995. Taking petrologic pathways toward understanding Rabaul's restless caldera. *Eos, Transactions, American Geophysical Union* **76**, 171, 180.

157. Blevin, P L, Chappell, B W, and Allen, C M, 1996. Intrusive metallogenic provinces in eastern Australia based on granite source and composition. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **87**, 281-290.

158. Chappell, B W, 1996. Compositional variation within granite suites of the Lachlan Fold Belt: its causes and implications for the physical state of granite magma. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **87**, 159-170.

159. Chappell, B W, 1996. Magma mixing and the production of compositional variation within granite suites: evidence from the granites of southeastern Australia. *Journal of Petrology* **37**, 449-470.

160. Sha, L -K, and Chappell, B W, 1996. A kinetic model for three-site intracrystalline ordering-disordering in minerals. *Geochimica et Cosmochimica Acta* **60**, 2075-2086.

161. Sha, L -K, and Chappell, B W, 1996. Two-site multi-cation ordering-disordering in minerals; an alternative kinetic model. *American Mineralogist* **81**, 881-890.

162. Allen, C M, Wooden, J L, and Chappell, B W, 1997. Late Paleozoic crustal history of central coastal Queensland interpreted from geochemistry of Mesozoic plutons: the effects of continental rifting. *Lithos*, **42**, 67-88.

163. Bryant, C J, Arculus, R J, and Chappell, B W, 1997. Clarence River Supersuite: 250 Ma cordilleran tonalitic I-type intrusions in eastern Australia. *Journal of Petrology* **38**, 975-1001.

164. King, P L, White, A J R, Chappell, B W, and Allen, C M, 1997. Characterization and origin of aluminous A-type granites from the Lachlan Fold Belt, southeastern Australia. *Journal of Petrology* **38**, 371-391.

165. Sha, L -K, and Chappell, B W, 1997. Multi-site order-disorder kinetics in crystalline solids: a generalized formulation. *American Mineralogist* **82**, 325-336.

166. Chappell, B W, and White, A J R, 1998. Development of P-rich granites by sequential restite fractionation and fractionational crystallisation: the Koetong Suite in the Lachlan Fold Belt. *Acta Universitatis Carolinae, Geologica* **42**, 23-27.

167. Sha, L -K, and Chappell, B W, 1998. Contribution of feldspars to the whole-rock phosphorus budget of I- and S-type granites: a quantitative estimation. *Acta Universitatis Carolinae, Geologica* **42**, 125-128.

168. Wyborn, D, and Chappell, B W, 1998. Chemical behaviour during fractionation of felsic granites from western Tasmania, Australia. *Acta Universitatis Carolinae, Geologica* **42**, 189-193.

169. Chappell, B W, 1998. Tectonic evolution of the eastern Australian fold belts from a granite-based perspective: 1998 Mawson Lecture. *The Australian Geologist* (in press).

170. Chappell, B W, 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* (in press).

171. White, A J R, Chappell, B W, and Wyborn, D, 1999. Application of the restite model to the Deddick Granodiorite and its enclaves: a re-interpretation of the observations and data of Maas *et al.* (1998). *Journal of Petrology* (in press).

172. Chappell, B W, Bryant, C J, Wyborn, D, White, A J R, and Williams, I S, 1999. High- and low-temperature I-type granites. *Resource Geology* (in press).

ABSTRACTS

1. Chappell, B W, Bailey, J C, Joyce, A S, and Rhodes, J M, 1967. Studies on granitic rocks of eastern Australia. In: *International Council of Scientific Unions, Upper Mantle Project; Second Australian Progress Report, 1965-67.* Ringwood, A E, (compiler), pp. 146-147. Australian Academy of Science. Canberra, Australia.

2. White, A J R, Chappell, B W, and Capp, A C, 1967. The Berridale Batholith. In: *International Council of Scientific Unions, Upper Mantle Project; Second Australian Progress Report, 1965-67.* Ringwood, A E, (compiler) pp. 148. Australian Academy of Science. Canberra, Australia, 1967.

3. Rhodes, J M, and Chappell, B W, 1971. Chemical investigation of the role of fractional crystallisation in the Cox's River intrusion, New South Wales. *Eos, Transactions, American Geophysical Union* **52**, 374.

4. O'Neil, J R, and Chappell, B W, 1975. A stable isotope study of the Berridale Batholith, southeastern Australia. *Eos, Transactions, American Geophysical Union* **56**, 473.

5. White, A J R, and Chappell, B W, 1976. Ultrametamorphism and granitoid genesis. 25th *International Geological Congress, 25th, Sydney, 1976. Abstracts, Vol. 3, Symposium* **102.2**, 674-675.

6. Compston, W, and Chappell, B W, 1978. Estimation of source Rb/Sr for individual igneous-derived granitoids and the inferred age of the lower crust in southeast Australia. 4th International Conference, Geochronology, Cosmochronology and Isotope Geology, Aspen, Colorado, August 20-25, 1978. *Short Papers, 79-81, U.S. Geological Survey Open-File report* **78-101**.

7. Perfit, M R, Arculus, R J, Johnson, R W, and Freeman, R S, 1978. Mineralogy, major, trace and isotope chemistry of volcanic rocks from the Tabar-to-Feni islands, Papua New Guinea; an alkalic island arc?. *Geological Society of America, Abstracts with Programs* **10**, 470.

8. Arculus, R J, Ferguson, J, Knutson, J, and Chappell, B W, 1979. Petrochemistry of crustal and upper mantle nodules from kimberlite pipes of southeast Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1979/2**, 1-2.

9. Chappell, B W, 1979. Granites as images of their source rocks. *Geological Society of America, Abstracts with Programs* **11**, 400.

10. Frey, F A, and Chappell, B W, 1979. Granites from Southeast Australia; constraints on source mineralogy and composition imposed by rare earth element abundances. *Geological Society of America, Abstracts with Programs* **11**, 428.

11. White, A J R, and Chappell, B W, 1979. Delegate breccia pipe: latest data and interpretations. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1979/2**, 98-99.

12. Wyborn, L A I, and Chappell, B W, 1979. Geochemical evidence for the existence of a pre-Ordovician sedimentary layer in south-eastern Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1979/2**, 104.

13. Wyborn, L, Chappell, B W, and Wyborn, D, 1979. The Lachlan Fold Belt - Early Palaeozoic links with Antarctica. *Journal of the Geological Society of Australia* **26**, 277..

14. Silver, L T, Williams, I S, Woodhead, J A, and Chappell, B W, 1980. Uranium and thorium endowment, distribution and mobilization in a uraniferous Precambrian granite. *Geological Society of America, Abstracts with Programs* **12**, 522.

15. Whitten, E H T, and Chappell, B W, 1981. Basement composition determined from post-orogenic granitoid compositions. In: Uppsala Caledonide Symposium (UCS); (With Pre- and Post-Symposium Excursions). *Terra Cognita* **1**, 81.

16. Arculus, R J, McCulloch, M, Jackson, I, Chappell, B W, Ferguson, and J, Smith, D, 1982. Trace element, isotopic and seismic velocity characteristics of eclogites and other inclusions derived from the lower crust of southern Australia and the Colorado Plateau. In: F.I.E.C. (First International Eclogite Conference) Excursions and Abstracts. *Terra Cognita* **2**, 301.

17. Chappell, B W, and White, A J R, 1982. I- and S-type granitoids in the Lachlan Fold Belt, southeastern Australia. *Proceedings of Symposium on Geology of Granites and their Metallogenetic Relations, Nanjing, China, 26 October-9 November, 1982*, pp. 8-9.

18. Chappell, B W, Compston, W, McCulloch, M T, and Williams, I S, 1982. Chemical and isotopic characterization of S-type granitoids in the Lachlan fold belt, southeastern Australia. In: Allegre-C J, and Didier J, (eds) Colloque International "*Geochimie et Petrologie Des Granitoides", 39, C.N.R.S. Paris, France.*

19. Liew, T C, McCulloch, M T, Page, R W, Chappell, B W, and McDougall, I, 1982. A Nd, Sr and U-Pb zircon isotopic study of the granitoid batholiths of Peninsular Malaysia. In: *Fifth International Conference on Geochronology, Cosmochronology and Isotope Geology, Abstracts*, pp. 215-216.

20. McCulloch, M T, Chappell, B W, and Hensel, H D, 1982. Nd and Sr isotope relationships in granitic rocks of the Tasman fold belt eastern Australia. In: *Fifth International Conference on Geochronology, Cosmochronology and Isotope Geology, Abstracts*, pp. 246-247.

21. White, A J R, Collins, W J, and Chappell, B W, 1982. Influence of melt composition on trace element abundances in granites. *Proceedings of Symposium on Geology of Granites and Their Metallogenetic Relations, Nanjing, China, 26 October-9 November, 1982*, pp. 73.

22. Arculus, R J, McCulloch, M T, Chappell, B W, Taylor, S R, Ferguson, J, Jackson, I, 1983. The nature of the lower crust; chemical, isotopic and seismic velocity characteristics. *Geological Society of Australia, Abstracts* **9**, 174-175.

23. Beams, S D, Chappell, B W, and White, A J R, 1983. Nepheline and quartz-bearing syenite at Jingera rock complex, Southeast Australia. *Geological Society of Australia, Abstracts* **9**, 296.

24. Jaques, A L, Lewis, J D, Gregory, G P, Ferguson, J, Smith, C B, Chappell, B W, and McCulloch, M T, 1983. The ultrapotassic, diamond-bearing rocks of the West Kimberley region, Western Australia. *Geological Society of Australia, Abstracts* **9**, 286-287.

25. Johnson, R W, Jaques, A L, Hickey, R L, McKee, C O, and Chappell, B W, 1983. Low-TiO (sub 2) basalts of Manam Island, Papua New Guinea; petrogenesis of an island-arc volcano. *Geological Society of Australia, Abstracts* **9**, 145-146.

26. Liew, T C, McCulloch, M T, Page, R W, and Chappell, B W, 1983. Granitoid batholiths and crustal evolution; implications from a Nd-Sr isotopic and U-Pb zircon study of peninsular Malaysian granitoids. *Geological Society of Australia, Abstracts* **9**, 188-190.

27. McCulloch, M T, Chappell, B W, Hensel, H D, and Compston, W, 1983. Nd and Sr isotope relationships in Paleozoic granitic rocks of south eastern Australia. *Geological Society of Australia, Abstracts* **9**, 187-188.

28. Reid, E J, Stewart-Richardson, D, and Chappell, B W, 1983. Petrogenesis of the Murrumbucka Tonalite; a granitoid with both I- and S-type character. *Geological Society of Australia, Abstracts* **9**, 179-181.

29. Smith, I E M, and Chappell, B W, 1983. Nature and origin of the undersaturated rocks of the Mt. Dromedary Complex. *Geological Society of Australia, Abstracts* **9**, 295.

30. Borg, S G, Chappell, B W, McCulloch, M T, Stump, E, Wyborn, D, and Holloway, J R, 1984. Compositional polarity of granitoids with implications to regional geology, northern Victoria Land, Antarctica. *Geological Society of America, Abstracts with Programs* **16**, 450.

31. Chappell, B W, and Sawka, W N, 1984. Vertical distribution of radioactivity in different types of granite crust; implications to heat flow in the Sierra Nevada Batholith, USA and the Lachlan fold belt, Australia. *Geological Society of America, Abstracts with Programs* **16**, 468.

32. Kistler, R W, Chappell, B W, Peck, D L, and Bateman, P C, 1984. Strontium isotopic variation in the Tuolumne intrusive suite, central Sierra Nevada, California. *Geological Society of America, Abstracts with Programs* **16**, 560.

33. Sawka, W N, and Chappell, B W, 1984. Compositionally zoned plutons by double-diffusive sidewall fractionation processes; evidence from the Palisade Crest Suite, central Sierra Nevada, California. In: Geoscience in the Development of Natural Resources. *Geological Society of Australia, Abstracts* **12**, 474.

34. Sawka, W N, Chappell, B W, and Kistler, RW, 1984. Compositionally zoned plutons by double-diffusive sidewall fractionation processes; evidence from the Palisade Crest Suite, central Sierra Nevada, California. *Geological Society of America, Abstracts with Programs* **16**, 645.

35. Whitten, E H T, and Chappell, B W, 1984. Suites within a granitoid batholith; a quantitative justification based on the Lachlan fold belt, SE Australia. In: Tezisy; 27-y Mezhdunarodnyy Geologicheskiy Kongress, Abstracts, 27th International Geological Congress. Report of the Session - International Geological Congress, **27**, 489.

36. Chappell, B W, and White, A J R, 1985. Granites and the Victorian lithosphere. In: Vandenberg, A H M, (ed.) *The Victorian Lithosphere: a Symposium*. Geological Society of Australia, Victorian Division, Melbourne, pp. 10-11.

37. Sawka, W N, and Chappell, B W, 1985. Compositional variations and equilibrium in REE, U and Th acceptor minerals during I-type granite differentiation, Palisade Crest Suite, central Sierra Nevada Batholith, California. *Geological Society of America, Abstracts with Programs* **17**, 708.

38. Silver, L T, Woodhead, J A, Williams, I S, and Chappell, B W, 1985. On late immiscible Fe-rich melt separation during crystallization of highly differentiated siliceous granites. *Fluid Inclusion Research*, **18**, 380.

39. Silver, L T, Woodhead, J A, Williams, I S, and Chappell, B W, 1985. On late immiscible Fe-rich melt separation during crystallization of highly differentiated siliceous granites. *Geological Society of America, Abstracts with Programs* **17**, 717.

40. White, A J R, and Chappell, B W, 1985. Chemical evidence for different sources of granite magmas. *Geological Society of America, Abstracts with Programs* **17**, 749.

41. Hergt, J M, Chappell, B W, McCulloch, M T, and McDougall, I, 1986. Geochemical and isotopic constraints of the genesis of Jurassic dolerites of Tasmania. *Terra Cognita* **6**, 183.

42. Jaques, A L, Sun, S -S, and Chappell, B W, 1986. Geochemistry of the Argyle lamproite pipe. *Geological Society of Australia, Abstracts* **16**, 51-53.

43. Kerr, I D, Jaques, A L, Lucas, H, Sun, S -S, and Chappell, B W, 1986. Diamond-bearing alkaline intrusions from Wandagee, Carnarvon Basin, Western Australia. *Geological Society of Australia, Abstracts* **16**, 54-56.

44. Sawka, W N, Frost, T P, and Chappell, B W, 1986. Contrasting trace element abundances in granitoid associated mafic inclusions (enclaves) and mafic intrusions from the eastern Sierra Nevada Batholith, CA. In: AGU 1986 Spring Meeting; Abstracts, *Eos, Transactions, American Geophysical Union* **67**, 384.

45. Sinton, J M, Liu, L, Taylor, B, and Chappell, B W, 1986. Petrology, magmatic budget and tectonic setting of Manus back-arc basin lavas. In: AGU 1986 Spring Meeting. *Eos, Transactions, American Geophysical Union* **67**, 377-378.

46. Whalen, J B, Currie, K L, and Chappell, B W, 1986. A-type granites; geochemical characteristics and discrimination. In: 1986 Joint Annual Meeting of GAC, MAC and CGU. Program With Abstracts - *Geological Association of Canada, Mineralogical Association of Canada, Canadian Geophysical Union Joint Annual Meeting*, 11, 144.

47. Wyborn, L A I, Chappell, B W, and Wyborn, D, 1986. Primary magmatic control on the distribution of Sn deposits of the Lachlan Fold Belt in N.S.W. and Victoria. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1986/10**, 78-79.

48. Ewart, A, Chappell, B W, and Menzies, M, 1987. Petrogenesis of the eastern Australian Cainozoic volcanic provinces. *Terra Cognita*, **7**, 613.

49. Silver, L T, James, E W, and Chappell, B W, 1987. Regional geologic setting of the Cajon Pass deep drillhole. In: AGU 1987 Fall Meeting. *Eos, Transactions, American Geophysical Union* **68**, 1489.

50. Whalen, J B, Currie, K L, and Chappell, B W, 1987. The Topsails intrusive suite; implications for the geochemical discrimination and tectonic setting of A-type granites. *Geological Society of America, Abstracts-with Programs* **19**, 888.

51. Duggan, M B, Knutson, J, and Chappell, B W, 1988. Petrology of the Warrumbungle Volcano, New South Wales. *Geological Society of Australia, Abstracts* **21**, 120.

52. Ewart, A, Chappell, B W, and Menzies, M, 1988. Petrogenesis of the eastern Australian Cainozoic volcanic provinces. *Geological Society of Australia, Abstracts* **21**, 130.

53. Silver, L T, James, E W, and Chappell, B W, 1988. Geologic insights from the DOSSEC Cajon Pass deep drillhole, San Bernardino Co., Calif. *Geological Society of America, Abstracts with Programs* **20**, 231-232.

54. Stephenson, P J, and Chappell, B W, 1988. The geology and petrology of the Palm Islands, north Queensland. *Geological Society of Australia, Abstracts* **21**, 377-378.

55. Stephenson, P J, Chappell, B W, and Frost, M T, 1988. Aspects of the geology and petrology of arfvedsonite granites, Hinchinbrook Island, north Queensland. *Geological Society of Australia, Abstracts* **21**, 379-380.

56. Williams, I S, Chen, Y, Chappell, B W, and Compston, W, 1988. Dating the sources of Bega Batholith granites by ion microprobe. *Geological Society of Australia, Abstracts* **21**, 424.

57. Wyborn, L A I, Wyborn, D, Chappell, B W, Sheraton, J W, Tarney, J F, Collins, W J, and Drummond, B J, 1988. Geological evolution of granite compositions with time in the Australian continent - implications for tectonic and mantle processes. *Geological Society of Australia, Abstracts* 21, 434-435.

58. Chappell, B W, 1989. Paleozoic granites and plate tectonics. In: *28th International Geological Congress, Abstracts, International Geological Congress, Abstracts--Congres Geologique Internationale, Resumes* **28**, 1.262-1.263.

59. Chen, Y D, Price, R C, White, A J R, and Chappell, B W, 1989. Mafic inclusions from granites of the Glenbog Supersuite, southeastern Australia. In: AGU 1988 Fall Meeting, Late Abstracts, *Eos, Transactions, American Geophysical Union* **70**, 604.

60. Rogerson, R J, Hilyard, D B, Finlayson, E J, Johnson, R W, McKee, C O, Chappell, B W, Price, R C, Nion, S T S, Joseph, L, Sumaiang, R, Duguman, J, and Patia, H, 1989. The geology and mineral resources of Bougainville and Buka islands, Papua New Guinea. *Memoir - Geological Survey of Papua New Guinea.* P: 217, 16.

61. Carr, P F, Jones, B G, and Chappell, B W, 1990. The Marulan Batholith: an atypical group of Early Devonian granitoids from the Eastern Lachlan Fold Belt. *Geological Society of Australia, Abstracts* **25**, 258.

62. Champion, D C, Bultitude, R J, and Chappell, B W, 1990. Geochemistry of Late Palaeozoic, felsic I- and S-type tin granites of the Mt Surprise-Cooktown area, north Queensland. *Geological Society of Australia, Abstracts* **25**, 275.

63. Champion, D C, Chappell, B W, and McCulloch, M T, 1990. Granites from the Hodgkinson Province, north Queensland; origin and implications for crustal evolution: isotopic and geochemical evidence. *Geological Society of Australia, Abstracts* **27**, 17.

64. Chappell, B W, 1990. Granites and tectonics. *Geological Society of Australia, Abstracts* **25**, 260-261.

65. Chappell, B W, 1990. S-type granites of the Wagga Batholith, SE Australia; the production of felsic granites by sequential restite fractionation and fractional crystallization. *Geological Society of America, Abstracts with Programs* **22**, 243.

66. Chappell, B W, and McCulloch, M T, 1990. Possible mixed source rocks in the Bega Batholith: constraints provided by combined chemical and isotopic studies. *Geological Society of Australia, Abstracts* **27**, 17.

67. Chappell, B W, and White, A J R, 1990. Tin granites: their evolution from fertile sediments by partial melting and fractional crystallisation. Frontiers in Ore Deposit and Exploration Studies. R.L. Stanton Symposium, 7 February, 1990, Convened by R.R. Large and Held During the 10th AGC, Hobart, 1990. Hobart: *Geological Society of Australia*, 17-18.

68. Chappell, B W, and White, A J R, 1990. Tin granites: their evolution from fertile sediments by partial melting and fractional crystallisation. *Geological Society of Australia, Abstracts* **25**, 307-308.

69. Corlett, G, Chappell, B W, McCulloch, M T, and Woodhead, J D, 1990. The origin of rhyolite in the Taupo Volcanic Zone, New Zealand; a strontium, neodymium, lead and oxygen isotope study. *Geological Society of Australia, Abstracts* **27**, 22.

70. Knott, D C, Saleeby, J B, Taylor, H P Jr, and Chappell, B W, 1990. Petrology of the Early Cretaceous Sierra Nevada Batholith; the Stokes Mountain region, CA. In: AGU 1990 Fall Meeting. *Eos, Transactions, American Geophysical Union* **71**, 1576.

71. Williams, I S, Compston, W, Chappell, B W, Crook, K A W, and Chen, Y D, 1990. Untangling the sources of granites by dating inherited zircons. *Geological Society of Australia, Abstracts* **27**, 112.

72. Blevin, P L, and Chappell, B W, 1991. Relationships between granites and mineral deposits in the Lachlan Fold Belt. *Geological Society of Australia, Abstracts* **29**, 4.

73. Blevin, P L, and Chappell, 1991. Some fundamental parameters in granitoid metallogeny: an eastern Australian perspective. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 10.

74. Carr, P F, Chappell, B W, and Jones, B G, 1991. Geochemical contrasts between intersecting Devonian and Carboniferous magmatic belts in the eastern Lachlan Fold Belt. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 20.

75. Champion, D C, Chappell, B W, and Bultitude, R J, 1991. Petrogenesis of felsic I-type granites: an example from far north Queensland. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 21.

76. Chappell, B W, 1991. Tectonic evolution of the Lachlan Fold Belt: petrological constraints. *Geological Society of Australia, Abstracts* **29**, 7.

77. Chappell, B W, and White, A J R, 1991. Compositional relationships of S- and I-type granites in the Lachlan Fold Belt. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 22.

78. Ewart, A, Schon, R W, and Chappell, B W, 1991. The Cretaceous silicic volcanic province of eastern Queensland, Australia: a segment of the S.W. Pacific Rift related province. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 34.

79. Hill, R I, Chappell, B W, and Campbell, I H, 1991. Late Archaean granitoids of the southeastern Yilgarn Block, Western Australia: age, geochemistry, and origin. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 46.

80. McCulloch, M T, Woodhead, J D, and Chappell, B W, 1991. Pb isotopic evidence for deep crustal-scale fluid transport during granite petrogenesis. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 64.

81. Rudnick, R L, McDonough, W F, and Chappell, B W, 1991. Cratonic and oceanic lithospheric mantle beneath northern Tanzania. In: Fifth International Kimberlite Conference, Extended Abstracts, *Proceedings of the International Kimberlite Conference* **5**, 344-346.

82. Stephenson, P J, Chappell, B W, McCulloch, M T, Frost, M T, and Reid, E, 1991. The geology and petrology of arfvedsonite granites, Hinchinbrook Island, north Queensland. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 102.

83. White, A J R, and Chappell, B W, 1991. Field and petrographic relationships of S- and I-type granites in the Lachlan Fold Belt. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 113.

84. White, A J R, Wyborn, D, and Chappell, B W, 1991. A granite classification for the economic geologist. *Geological Society of Australia, Abstracts* **29**, 57.

85. Williams, I S, Chappell, B W, and Chen, Y D, 1991. Inherited and detrital zircons - vital clues to the granite protoliths and igneous history of southeastern Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 114.

86. Williams, I S, Chappell, B W, McCulloch, M T, and Crook, K A W, 1991. Inherited and detrital zircons - clues to the early growth of crust in the Lachlan Fold Belt. *Geological Society of Australia, Abstracts* **29**, 58.

87. Wyborn, D, White, A J R, and Chappell, B W, 1991. Enclaves in the S-type Cowra Granodiorite. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* **1991/25**, 117.

88. Allen, C M, and Chappell, B W, 1992. Association of I-type granites with rift related alkalic magmatism in central coastal Queensland, Australia. *Geological Society of America, Abstracts with Programs* **24**, 43.

89. Carr, P F, Chappell, B W, and Jones, B G, 1992. Geochemical contrasts between intersecting Devonian and Carboniferous magmatic belts in the eastern Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 487.

90. King, P L, Chappell, B W, Blevin, P L, Allen, C M, and White, A J R, 1992. An example of a fractionated A-type granite from the Lachlan fold belt, eastern Australia. *Geological Society of America, Abstracts with Programs* **24**, 43.

91. King, P L, Chappell, B W, White, A J R, and Williams, I S, 1992. A-type granites of the Lachlan fold belt, eastern Australia. In: AGU 1992 Spring Meeting. *Eos, Transactions, American Geophysical Union* **73**, 14, Supplement, 346-347.

92. McCulloch, M T, Woodhead, J D, and Chappell, B W, 1992. Pb isotopic evidence for deep crustal-scale fluid transport during granite petrogenesis. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 494.

93. Stephenson, P J, Chappell, B W, McCulloch, M, Frost, M T, and Reid, E, 1992. The geology and petrology of arfvedsonite granites, Hinchinbrook Island, N Queensland. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 501.

94. Williams, I S, Chappell, B W, Chen, Y D, and Crook, K A W, 1992. Inherited and detrital zircons - vital clues to the granite protoliths and early igneous history of southeastern Australia. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **83**, 503.

95. Chappell, B W, 1993. Heat producing elements in granites of southeastern Australia. *Australian Geological Survey Organisation, Record* **1993/72**, 4.

96. Williams, I S, Chappell, B W, Crook, K A W, and Nicoll, R S, 1994. In search of the provenance of the Early Palaeozoic flysch in the Lachlan Fold Belt, southeastern Australia. *Geological Society of Australia, Abstracts* **37**, 464.

97. Blevin, P L, Allen, C M, Bryant, C J, and Chappell, B W, 1995. A metallogenic template for eastern Australia based on granite source and evolution. *United States Geological Survey Circular*, **1129**, 25-26.

98. Chappell, B W, 1995. Causes of compositional variation within granite suites. *United States. Geological Survey, Circular*, **1129**, 34.

99. Allen, C M, and Chappell, B W, 1996. The petrogenesis of the Mesozoic rocks, Bowen region, Queensland, and changes of tectonic setting from 145 to 100 Ma. *Geological Society of Australia, Abstracts* **43**, 16-21.

100. Blevin, P L, and Chappell, B W, 1996. Controls on the distribution and character of the intrusive-metallogenic provinces of eastern Australia. *Geological Society of Australia, Abstracts* **41**, 42.

101. Blevin, P L, Candela, P A, and Chappell, B W, 1996. Magmatic controls on ore metal ratios across the Cu-Mo(Au) "porphyry" spectrum. *Geological Society of Australia, Abstracts* **41**, 41.

102. Blevin, P L, and Chappell, B W, 1996. Internal evolution and metallogeny of Permo-Triassic high-K granites in the Tenterfield-Stanthorpe region, southern New England Orogen, Australia. *Geological Society of Australia, Abstracts* **43**, 94-100.

103. Blevin, P L, and Chappell, B W, 1996. Permo-Triassic granite metallogeny of the New England Orogen. *Geological Society of Australia, Abstracts* **43**, 101-103.

104. Bryant, C J, Arculus, R J, and Chappell, B W, 1996. Clarence River Supersuite: primitive I-type granites of eastern Australia. *Geological Society of Australia, Abstracts* **41**, 64.

105. Gust, D A, Blevin, P L, Chappell, B W, and Stephens, C J, 1996. Early Mesozoic magmatism of the New England Orogen: space, time, and compositional relationships. *Geological Society of Australia, Abstracts* **43**, 224-227.

106. Sha, L -K, and Chappell, B W, 1996. Phosphorus behaviour in I- and S-type granitic magmas: examples from the Lachlan Fold Belt, Australia. *Geological Society of Australia, Abstracts* **41**, 382.

107. Allen, C M, Wyborn, D, and Chappell, B W, 1998. Plutonic rocks of the New England Orogen north of Rockhampton: Are they Cordilleran Style? *Australian Geological Survey Organisation, Record* **1998/33**, 19.

108. Chappell, B W, 1998. Basement of the Lachlan Fold Belt: the evidence from S-type granites. *Australian Geological Survey Organisation. Record* **1998/2**, 34-37.

109. Chappell, B W, 1998. I-type granites of the Lachlan Fold Belt and their source rocks. *Geological Society of Australia, Abstracts* **49**, 76.

110. Chappell, B W, 1988.The restite model: a revolution in petrogenesis. *Australian Geological Survey Organisation, Record* **1998/33**, 26.

111. Chappell, B W, and White, A J R, 1998. Compositional variation in the S-type granites of the Lachlan Fold Belt and its causes. *Geological Society of Australia, Abstracts* **49**, 77.

112. Flood, R H, Forrest, J, and Chappell, B W, 1988. Plutonic suite recognition in the Bega and Moruya Batholiths using a multivariate extension of entropy analysis of the chemical data base. *Australian Geological Survey Organisation, Record* **1998/33**, 30.

113. Williams, I S, and Chappell, B W, 1998. Crustal evolution in Southeastern Australia: A zircon viewpoint. *Australian Geological Survey Organisation, Record* **1998/33**, 44

THESES

1. Chappell, B W, 1959. The geology of the Tamworth-Manilla-Bendemeer district, New South Wales. *University of New England. B.Sc. Honours Thesis.*

2. Chappell, B W, 1961. The stratigraphy and structural geology of the Manilla-Moore Creek district, N.S.W. and petrology of the greywackes of the Baldwin Formation. *University of New England. M.Sc. Thesis.*

3. Chappell, B W, 1966. Petrogenesis of the granites at Moonbi, New South Wales. *Australian National University, Ph.D. Thesis.*

4. Chappell, B W, 1990. Chemical evolution and origin of granites in the Lachlan Fold Belt. *Australian National University, D.Sc.* Thesis.

PLUTONIC ROCKS OF THE NEW ENGLAND OROGEN NORTH OF ROCKHAMPTON: ARE THEY CORDILLERAN STYLE?

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Whereas the first order petrogenesis of granites in the Lachlan Fold Belt is still being debated, the New England Orogen (NEO) granites are generally accepted to be subduction zone related. In the northernmost part of the NEO (that section north of Rockhampton), this model can be tested on plutons ranging in age from Devonian to Cretaceous by comparing their compositions to batholithic rocks known to have formed above subduction zones, like the Mesozoic Peninsular Ranges batholith of California and Mexico.

The NEO, in structural terms, includes those rocks affected by the Late Permian-Triassic Hunter-Bowen Orogeny. The style of the deformation in the northernmost NEO was thin- to thick- skinned westward thrusting. In terrane terms, the basic element of the Orogen, found along its entire length, is Late Devonian-Early Carboniferous forearc deposits. Backarc deposits of the same age are preserved in the Drummond Basin west of the NEO. Separating the Drummond Basin from the NEO is the Permian-Triassic Bowen Basin. Its eastern margin was deformed by Hunter-Bowen thrusting which helped expose the Connors Arch, a middle crustal block of mostly granite that defines the western margin of the NEO at its northern end.

LATE DEVONIAN-EARLY CARBONIFEROUS

Although sedimentary rocks of this age are widespread, felsic to intermediate igneous rocks of this age are rare. Those found in the forearc deposits are dominantly mafic. The remainder lie in the Drummond Basin (Henderson *et al.*, 1998) and relatively little geochemical work has been published on these. Taking inheritance into account, these mostly volcanic tuffs crystallised between 350 and 340 Ma. This is a compositionally restricted suite. Plutons of somewhat greater age (385-366 Ma; Crouch *et al.*, 1995) occur in an uplifted basement block in the Drummond Basin (Anakie Inlier).

LATE CARBONIFEROUS-PERMIAN

A large portion of the northern NEO are igneous rocks of this age. Plutonic and volcanic rocks occur in the Connors and Auburn arches, and in the Drummond Basin. Volcanic rocks of this age also floor the Bowen Basin. Before orogeny, volcanic rocks blanketed the northern NEO. Compositions are diverse; plutonic rocks are dominated by granodioritic-tonalitic compositions. A suite of similar rocks of Late Permian age, called the Clarence River Suite, occurs at the southwest edge of the Clarence Morton Basin (Bryant *et al.*, 1997) in the southern NEO.

TRIASSIC

Triassic plutonic and volcanic rocks occur in the Whitsunday Province and near Bowen (Ewart *et al.*, 1992) and in the Gayndah region (Stephens, 1991). Stephens has subdivided this age group into older and younger series, where the older tends to be intermediate, and the younger, felsic and/or bimodal.

CRETACEOUS

Cretaceous igneous rocks occur in the Whitsunday Province, and in the Connors Arch. Rocks 125-100 Ma rocks occur in both areas. Plutonic rocks are dominantly true granites; volcanic rocks are bimodal. In contrast, Early Cretaceous rocks (>125 Ma) are restricted to the Connors Arch and these are intermediate (Allen *et al.*, 1997). Cretaceous plutons also occur near Noosa, and at Mount Dromedary (southern coastal NSW).

The occurrence of fore- and backarc deposits of Late Devonian-Early Carboniferous age leaves little doubt that subduction was locally active, however it is interesting how little evidence of "an arc" can be found. As presently understood, igneous activity at this time was dominated by dispersed felsic volcanism. The bulk of plutonic rocks in the northern NEO, are distinctly younger (322-278 Ma; Allen *et al.*, 1998) and comprise three suites: the Urannah, the Bulgonunna, and the more minor Thunderbolt. Because of Hunter-Bowen thrusting, two structural levels of the same igneous pile are exposed. The Urannah Suite in the Connors Arch is mid-crustal based on Al-in-hornblende geobarometry, and the Bulgonunna Suite is subvolcanic. Bulgonunna igneous rocks overlie Drummond Basin sedimentary rocks and are essentially undeformed. When rock compositions of the two suites are compared, there are only subtle differences. The more oceanward and deeper Urannah is marginally more mafic on average. The Bulgonunna Suite is more continental in character having higher average concentrations of K, Ba, Rb, Pb, Th, U, Nb, Zr, Y La, Ce, Cr and Ga, and lower concentrations of Ca, Sr, Mn and Ni. The suites are almost indistinguishable with respect to Rb-Sr, Sm-Nd and Pb isotopes. For instance, the Urannah and Bulgonunna suites contain rocks with initial $^{87}Sr/^{86}Sr$ as calculated at 280 Ma of 0.704-0.707 (n=33 and 20, respectively) but the Urannah contains two samples more radiogenic than this (0.7085 and 0.7088).

As compared to the eastern and western Peninsular Ranges Batholith (PRB), the compositional difference between the Urannah and Bulgonunna rocks is less than between the wPRB and ePRB. Only CaO and Zr show more variability in the Queensland rocks. The wPRB contains very high Ba contents. Overall the Queensland rocks appear more continental in character with higher K_2O, Rb, Pb, U, Th and REE than PRB averages (using only rocks with 62-68 wt% SiO_2), but note they are generally less radiogenic with respect to Pb isotopes. The ePRB contains 1.5 times more Sr and half as much Y as the wPRB, but the Bulgonunna Suite contains somewhat lower average Sr, and 1.5 times as much Y as Urannah rocks. This is the critical difference between the two systems. The ePRB has been interpreted as derived from rocks where garnet was stable and involved continental lithosphere; whereas the wPRB is interpreted as derived from lithosphere relatively free of continental influence and where plagioclase was stable. The wPRB has initial $^{87}Sr/^{86}Sr$ of 0.7035-0.7060. The Urannah-Bulgonunna Supersuite shares many features with the wPRB. Modelling suggests that the dominant sources of these Queensland rocks were mafic lower crust of early Paleozoic to Neoproterozic age. Nd model ages range from 1270 to 800 Ma minus 2 extraordinary samples.

Unlike igneous rocks older than ~250 Ma, those younger are distinctly less radiogenic with respect to Rb-Sr, Sm-Nd and Pb isotopes (initial $^{87}Sr/^{86}Sr$ of 0.7030-0.7390). Their Nd model ages are 560-365 Ma. Moreover, their tectonic origins are less certain. Cretaceous rocks from the Whitsunday Province have been suggested to relate to opening of the Tasman Sea. For those rocks less than 125 Ma, this explains their bimodality, however the 145-125 Ma rocks tend to be intermediate and are more easily related to subduction. Note that the oldest seafloor in the Coral Sea is 65 Ma. We suggest that underplating related to formation of Australia's passive margin in the Neoproterozoic provided the sources for the Urannah and Bulgonunna suites. Sources of igneous rocks < 250 Ma were distinctly younger and may include basalts about the age of the crystallization events themselves.

REFERENCES

Allen, C M, Wooden, J L, and Chappell, B W, 1997. Late Paleozoic crustal history of central coastal Queensland interpreted from geochemistry of Mesozoic plutons: the effects of continental rifting. *Lithos* **42**, 67-88.

Allen, C M, Williams, I S, Stephens, C J, and Fielding, C R, 1998. Granite genesis and basin formation in an extensional setting: the magmatic history of the northernmost New England Orogen. *Australian Journal of Earth Sciences* **45**, in press.

Bryant, C J, Arculus, R J, Chappell, B W, 1997. Clarence River Supersuite: 250 Ma Cordilleran tonalitic I-type intrusions in eastern Australia, *Journal of Petrology* **38**, 975-1001.

Crouch, S B S, Withnall, I W, Tenison Woods, K, and Hayward, M A, 1995. Plutonic rocks of the southern Anakie Inlier. In: Withnall, I.W., Blake, P.R., *et al.* (eds). Geology of the southern part of the Anakie Inlier, central Queensland, pp. 95-115. *Queensland Geology* **7**.

Ewart, A, Schon, R W, Chappell, B W, 1992. The Cretaceous volcanic-plutonic province of central Queensland (Australia) coast--a rift related 'calc-alkaline' province. *Transactions of the Royal Society of Edinburgh* **83**, 327-345.

Henderson, R A, Davis, B K, and Fanning, C M, 1998. Stratigraphy, age relationships and tectonic setting of rift-phase infill in the Drummond Basin, central Queensland. *Australian Journal of Earth Sciences* **45**, 579-595.

Stephens, C J, 1991. The Mungore Cauldron and Gayndah Centre. Late Triassic large-scale silicic volcanism in the New England Fold Belt near Gayndah, southeast Queensland; *Ph.D. thesis, University of Queensland, Brisbane* (unpublished).

FROM GRANITES TO MINERAL EXPLORATION

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The work of Bruce Chappell and other granite researchers has meant that granites are no longer regarded as the areas of pink that you map up to the edge of. As a consequence, there is now a greater understanding of the relationship between the lower crust and metallogenic provinces. Whether a particular granite has mineralisation associated with it, depends on factors such as concentration of metal in the source rocks, initial and final water content of the magma, level of intrusion in the crust, amount of melt component, degree of fractionation, oxidation state and reactivity of wall rocks. Many of these factors are predetermined by composition of source rocks and conditions of partial melting – two themes which permeate much of Chappell and coworkers' research over the years.

The wealth of granite data now available allows the mineral explorationist to rank a regions prospectivity for granite hosted or granite sourced mineralisation. On a regional scale the chemical and mineralogical features of individual granite plutons produce characteristic airborne magnetic, radiometric and thematic mapping (TM) signatures. Screening the background granitic features allows potentially mineralised structures and alteration systems to be targeted. Field, petrographic and chemical studies of granite on a local scale provide an intimate understanding of the crustal and mineralisation history of a prospect area. Careful mapping of individual granite plutons and their relations to multi-generation dykes, hydrothermal alteration, breccia zones, structural fabric and vein sets can unravel timing relationships, an understanding of which is crucial in all phases of exploration. The methodology and working hypotheses developed by the granite researchers have important practical applications which can be utilized by lateral thinking explorationists. Some examples are:

GRANITES INHERIT THEIR CHARACTERISTICS FROM THEIR SOURCE REGION.

This can be applied more generally as a notion that genetic information is encapsulated within rocks. In an exploration context, careful observation of key rocks such as breccias, veins, alteration zones and regolith materials will often provide insights into a prospect's geological history, timing of mineralisation, and clues about the presence of a blind ore deposit.

CHOICE OF APPROPRIATE SAMPLE MEDIA WITH ACCURATE AND REPEATABLE GEOCHEMICAL ANALYSIS OPTIMISES INTERPRETATION OF RESULTS

Nowadays, it is universally accepted that precise chemical analysis, together with a large sample size to account for coarse grainsize, is required to delineate trends in the chemical variation of granites. This was not always the case, Bruce Chappell's sampling and analytical procedures have become the yardstick by which other chemical studies are measured. There are many parallels in exploration geochemistry, particularly when applied to gold and pathfinder elements. Very low levels of detection (down to ppb or ppt level) and collecting of bulk samples to avoid grainsize (i.e. nugget) effects are now the norm and have led to discoveries of ore.

DON'T IGNORE THE OBVIOUS

Closed minds about the uniformity of large areas of granite often meant that obvious geological features went undiscovered until granite areas were mapped. In a similar fashion, many mineral discoveries have been made after a resourceful geologist defies conventional wisdom and investigates prominent features in areas regarded up to that point as unprospective.

DATA PROCESSING AND PRESENTATION SYSTEMS PLAY A CRUCIAL ROLE IN THE PRESENTATION OF DATA

The bulk data generated by multielement analysis of granites quickly outgrew the data processing systems of the early 1970's. Similarly, data management systems have had to keep up with the enormous volume of data generated in mineral exploration. Today's exploration geologist at least has the advantage of off the shelf software and doesn't have to emulate Bruce Chappell and develop whole geochemical analytical, data manipulation and data presentation systems virtually from scratch.

THE CHAPPELL LEGACY

The growth in quantity and quality of geological and geochemical data over the past thirty years has been staggering. The geological community owes a great debt to research scientists such as Bruce Chappell who have been pathfinders in the collection, presentation and interpretation of high quality geochemical data, along the way contributing to the understanding of geological terranes and their related mineral deposits.

TRACE ELEMENTS IN ACCESSORY ZIRCON AND APATITE: APPLICATION TO PETROGENESIS AND MINERAL EXPLORATION

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The main target of this project is to determine the relationship between the chemical composition of zircon and apatite that occur in wide range of igneous rocks and mineral deposits, and the igneous systems from which they formed. These minerals concentrate many trace elements, and provide a record of the chemical environment through different stages of crystallisation (Nash, 1984; Shnukov *et al*, 1989; Evans and Hanson, 1993). The GEMOC laser-ablation ICPMS microprobe has allowed analysis of about 30 trace elements (including REE, Y, Sr, U, Th, Pb, Fe, Mn) from 30-50 µm spots on single zircon or apatite grains. This has provided fundamental trace element information on the chemical composition of those accessory minerals and their relation to rock-forming processes. Definition of discriminants will allow the recognition of zircons and apatites from specific rock types and styles of mineralisation, so that these grains might be recognised in the heavy mineral concentrates used in geochemical exploration for mineral deposits.

Representative samples of apatite have been selected from granites (from Australia and Norway), larvikites and pegmatites (Norway), diabases (Ukraine), as well as apatites from less common rock types such as carbonatites (Fen, Norway; Palabora, S.Africa; Kovdor, Russia; Mud Tank, Australia), jacupirangite (Kodal, Norway), and iron ore deposits (Kiruna, Sweden and Durango, Mexico). Trace-element signatures specific for apatite of different origins have been defined. The results indicate that the distribution of trace elements, especially REE, Y, Mn, Th, in apatite depends not only on the mineral structure, but on the abundance of these trace elements and the chemical characteristics of the melt or fluid reservoir where the apatite crystallised.

Particular attention has been paid to the study of primary magmatic apatites from granitoid rocks with the goal of determining how the chemical composition of this mineral reflects granite fractionation. The subsequent task was to determine whether apatite major and trace element geochemistry can be used to characterise granite suites related to Cu-Au mineralisation. The study is focused on Australian Proterozoic granite suites of the Mount Isa Inlier using the extensive AGSO granite collection. Preliminary results suggest that apatite is a sensitive indicator of the crystallisation environment and that the distribution of trace elements in apatite could be used as an additional tool to recognise highly fractionated and highly oxidised granitoids related to Cu-Au mineralisation.

REFERENCES

Evans, O C, and Hanson, G N, 1993, Accessory-mineral fractionation of rare-earth element (REE) abundances in granitoid rocks., *Chemical Geology*, **110**, 69-93.

Nash, W P, 1984, Phosphate minerals in terrestrial igneous and metamorphic rocks. In Nriagy, J. O. and Moore, P.B. (Ed.), Phosphate minerals, Berlin Heidelberg: Springer-Verlag, pp. 442.

Shnukov, S E, Cheburkin, A K, and Andreev, A V1989, Geochemistry of wide-spread coexisting accessory minerals and their role in investigation of endogenic and exogenic processes, *Geological Journal*, **2**, 107-114 (in Russian).

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THE METALLOGENY OF GRANITIC ROCKS

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Fundamental relationships between ore deposits and certain types of intrusive igneous rocks have long been known. These include the association of chalcophile-dominated mineralisation with diorites and granodiorites, and lithophile-dominated mineralisation with compositionally "specialised" granitic rocks. The relative oxidation state of mineralised intrusives was also known to be important, with Mo and Cu mineralisation associated with oxidised (magnetite-bearing) igneous rocks, and Sn and W with reduced (magnetite-free) rocks.

Integration of these basic relationships with mineral deposit and granite chemical databases for SE Australia have demonstrated the primacy of magmatic compositional parameters in determining ore element ratios in related mineralisation. Furthermore, these studies revealed that ore deposit types change systematically across the compositional spectrum observed within individual supersuites. The range of deposit types also varies according to the degree of the compositional evolution of the suite or supersuite. Thus the compositionally highly evolved Carboniferous I-types of North Queensland are associated with lithophile dominated deposits, while the less evolved Boggy Plain Supersuite are associated with chalcophile dominated deposits. Such relationships also provide a rational basis for the understanding of metal zonation on a district scale.

An enduring theme in the literature has been the concept that high metal inventories in magmas are required for mineralisation to occur. Marked enrichments and depletions in ore metal abundances within granitic magmas occur as a result of fractional crystallisation, and it is this process that is probably responsible for most of the variation in ore element abundances observed in granites (other than processes involving hydrothermal redistribution).

Other magmatic and hydrothermal processes may locally be important, but still require the operation of fractional crystallisation processes to work. One such example is the Mount Leyshon Au-polymetallic system where the timing of the introduction of the Au-Te-Bi ore assemblage along with Fe and S are most closely associated with dykes that contain abundant cognate xenoliths, and have textures indicating disequilibrium crystallisation and resorption. Here, overturning of a subvolcanic zoned magma chamber probably resulted in the re-dissolution of early crystallised sulfides and the liberation of chalcophile elements, Fe and S into an exsolving hydrothermal fluid.

Mineral deposits associated with granitic rocks are fundamentally polymetallic in character. Their metallogeny can however be considered in terms of a continuum in ore element ratios from chalcophile-dominated to lithophile dominated mineralisation in highly compositionally evolved granites. These relationships are evident at all scales from the regional to within individual deposits where variations in metal character can reflect the progress of crystallisation and volatile exsolution within single magma chamber. The polymetallic Mount Leyshon Au deposit (north Queensland) has early Mo mineralisation associated with rhyolitic intrusives cut by later Au-base metal mineralisation associated with andesitic to rhyodacitic dykes. This relationship is also born out regionally in deposits associated with compositionally similar intrusives.

The zoned and polymetallic nature of deposits associated with intermediate to felsic intrusives can therefore be systematised within a scheme that classifies magmas into suites and takes into account such factors as the degree of compositional evolution of the related granite series and its oxidation state.

The use of the suite concept, and an understanding of metal zoning at all scales, enables the regional distribution of mineralisation to be resolved, and for predictions to be made as to the probable distribution of similar mineralisation. The current level of exposure is also critical. Too deeply eroded batholiths lose the mineralised-upper portions of magma chambers. Erosional contrasts across the south west USA are reflected in differing W/Cu ratios of ore deposits, for example.

ARCHAEAN GRANITES OF THE YILGARN AND PILBARA CRATONS

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Archaean granites occur in a number of regions in Australia although are best known from the Pilbara and Yilgarn cratons in Western Australia. his paper compares and contrasts granites from the central and eastern parts of the Pilbara Craton (EPC) with those from the Eastern Goldfields Province (EGP), Yilgarn Craton. Geological and geochemical data used is from continuing AGSO-GSWA NGMA projects in the EGP and the Pilbara Craton (>1200 regional chemical analyses collected in conjunction with regional mapping and geochronology) supplemented with published data. The resulting geological, geochemical and geochronological data has been utilised to identify broad regional granite groups within the Pilbara and Yilgarn Cratons.

As typical examples of Archaean granite-greenstone terrains, both regions share many similarities, including overall trends in granite composition with time, however, a major contrast is the duration over which these compositions evolved. Granites (and orthogneisses) comprise approximately 60% and 75% of the EPC and EGP, respectively. Those of the Pilbara Craton, are largely confined to pronounced domal batholiths enveloped by often deep-rooted (> 8 km) synformal greenstone belts, while those in the EGP exhibit a more pronounced linear pattern of elongate batholiths and arcuate greenstone belts.

Both the greenstones and granites of the Pilbara Craton were formed episodically over an 800 Ma period, from ca. 3.6 Ga to younger than 2.8 Ga. Known periods of granite intrusion include ca. 3.47-3.41, ca. 3.33-3.31, 3.24, 3.1, 3.0-2.93 Ga, ca. 2.85 Ga and ca. 2.76 Ga with most volume relating to the 3.47-3.41, 3.3 and 3.0-2.93 Ga events. Granites from the first three periods appear to be at least temporally associated with volcanism. In contrast, available geochronology for the EGP indicates that >95% of the exposed granite-greenstone sequence developed over a much narrower interval, between 2.72 Ga and 2.63 Ga with the majority of the granites emplaced between 2.67-2.64 Ga. Indirect evidence (e.g., inherited zircons, Sm-Nd isotopic data), however, does suggest the presence of pre-existing felsic crust that may range in age from 3.3 Ga in the west to 2.8 Ga in the eastern part of the EGP. Felsic volcanism in the EGP overlaps with the older granites but appears to have ceased by 2.67, i.e., before the bulk of granite magmatism.

Although the cratons exhibit different pre-histories it is notable that they share a somewhat similar pattern of granite evolution. The early Pilbara granites (Ca. 3.45 Ga), best documented in the Shaw Batholith are similar to typical Archaean TTGs elsewhere. These rocks have an expanded silica range (62->70% SiO_2), are sodic, LREE-enriched, HREE- and Y-depleted, and Sr-undepleted with little or no Eu anomalies (Bickle *et al.*, 1993). Such compositions are consistent with derivation at high pressures (garnet stable) from a mafic crustal source (thickened crust or subducted slab). Available isotopic data suggest some minor contribution from pre-existing felsic crust (Bickle *et al.*, 1993). While the 3.3 Ga granites locally share many characteristics with the 3.45 Ga group (e.g., sodic, Sr-undepleted, Y-depleted granites of the Mt Edgar and Shaw batholiths), these granites tend to be more silica-rich (65-75% SiO_2) and do not appear to be as strongly HREE-depleted (Collins, 1993). The 3.3 Ga group also includes numerous granites that are potassic, often fractionated (65-77% SiO_2), Sr-depleted, and HREE-undepleted, such as those in the Corunna Downs Batholith (Davy, 1988). Clearly, these latter granites must represent crustal reworking, presumably over a range of pressures including those at which plagioclase was stable. The origin of the 3.3 Ga granites in the Mt Edgar Batholith is more equivocal; they could either represent new crust or, as suggested by Collins (1993), reworking of older TTG-type granites. Similar geochemical groups are present within the compositionally diverse post-3.3 Ga granites, especially the 3.0-2.93 Ga group. Granites of this age include a) a felsic (68-77% SiO_2) series characterised by high K_2O/Na_2O, generally high Rb/Sr and HREE-enrichments, b) a felsic (68-77% SiO_2), moderate to high K_2O/Na_2O group with low to intermediate HREE-enrichments and negative Eu anomalies (i.e., characteristics somewhat intermediate between the early 3.45 TTGs and the fractionated potassic group which presumably reflect reworking of a TTG-type source), c) rather mafic (high Mg, Mg#, Cr, Ni) but LILE-rich rocks that appear to represent the felsic derivatives of sanukitoids (i.e. a sanukitoid suite), and d) a group of highly felsic sub-alkaline granites with a distinctive anhydrous mineralogy (including a sodic clinopyroxene) and distinctive A-type compositions. The younger, 'Post-tectonic' 2.85 Ga granites such as the Cooglegong, Moolyella and Numbana granites are high-silica granites (>72% SiO_2) with high K_2O/Na_2O, Y and HREE contents, generally high to very high Rb/Sr, and large negative Eu anomalies. They are typically associated with Sn, and are chemically similar to other I-type 'tin' granites (e.g., north Queensland). The 2.76 Ga group is also diverse and includes small stocks of peraluminous, tourmaline-rich rocks of S-type character and more voluminous rocks of distinctly A-type composition. The geochemistry and available Sm-Nd data (Bickle *et al.*, 1989) indicate that derivation of the majority of the post-3.3 Ga granites appears to have involved a dominant component of pre-existing crust. Hence, in the EPC, the overall trend in evolution of granite composition with time is, (with notable exceptions such as the sanukitoids suite), to more potassic and LILE-enriched rocks, with an increasingly apparent signature of crustal reworking.

The EGP granites appear to have followed a similar evolutionary trend, and while true TTG-type granites appear to be largely absent from the EGP (and for that matter the rest of the Yilgarn Craton) their presence can be inferred through indirect evidence. Champion and Sheraton (1997) subdivided the EGP granites into two major (High- and Low-Ca) groups that together comprise over 60 percent and 20 percent, respectively, of the total granites, and three minor (High-HFSE, Syenitic and Mafic) geochemical groups. The High-Ca granites (2.72-2.66 Ga) are dominantly sodic, Sr-undepleted, and Y-depleted and are compositionally similar to TTGs, except that they have significantly higher LILE contents and more felsic compositions (68-77% SiO_2). Sr-depleted Y-undepleted granites are a subgroup that forms a geochemical continuum with the main granites of the High-Ca group, and in this and other aspects the High-Ca granites appear similar to the 3.3 Ga EPC granites. Sm-Nd data are mostly quite similar for the group (mostly 0.2 to 1.7). The origin of these granites requires the involvement of pre-existing felsic crust. The largely younger and clearly crustal-derived Low-Ca granites (2.66-2.63 Ga) are characterised by high-LILE, strong enrichments in the LREE and some of the HFSE, and compositions consistent with crystal fractionation. Like the High-Ca group, the Low-Ca group also includes both Y-undepleted and Y-depleted granites, although both subgroups are Sr-depleted. Notably, the Low-Ca granites exhibit a pronounced isotopic polarity spanning six ε_{Nd} units, from primitive in the east (+2.0), to evolved (-4.5) in the west of the EGP (Champion and Sheraton, 1997) requiring the existence of an older tonalitic crust, probably not unlike the 3.45 Ga TTG granites of the EPC. The isotopic data suggests that the High- and Low-Ca granites were derived from distinct source reservoirs. Other granite types in the EGP are volumetrically minor and include: a) the crustal-derived high SiO_2 (>74% SiO_2) High-HFSE group (2.685-2.66 Ga) with distinctive A-type characteristics but low LILE contents, especially Rb and Pb; b) a geochemically diverse but isotopically similar group of more mafic (<60 to >70% SiO_2) granites (2.69-2.65 Ga) that exhibit large between-suite variations in LILE and LREE; and c) younger syenites (2.65-2.64 Ga). ε_{Nd} values for the mafic granites and syenites overlap with those of the High-Ca granites but extend to more primitive values (3.0).

It is evident from the above that the granite types in both the Pilbara and Yilgarn cratons exhibit an overall tendency to become more potassic (higher LILE contents), but also more variable in composition with time. This reflects initial continental crustal growth and continual additions, and subsequent reworking to produce an increasingly mature and heterogeneous crust. This can either occur over a long period as for the Pilbara or very rapidly as is evident in the EGP. Regardless of the duration, the result is that TTG magmatism, often regarded as a voluminous characteristic of Archaean terrains, is, at the present exposure level, relatively poorly represented in both the Pilbara and Yilgarn cratons, particularly the latter. The change from TTG-type granites through to more typical felsic potassic LILE-rich granites is analogous to that documented for the Phanerozoic by Chappell and Stephens (1988) and illustrates the similarity in granite processes over time superimposed on a secular changing earth.

REFERENCES

Bickle, M J, Bettenay, L F, Chapman, H J, Groves, D I, McNaughton, N .J, Campbell, I H, and de Laeter, J R 1993. Origin of the 3500-3300 Ma calc-alkaline rocks in the Pilbara Archaean: isotopic and geochemical constraints from the Shaw Batholith. *Precambrian Research*, 60, 117-149.

Champion, D.C. and Sheraton, J.W. 1997. Geochemistry and Nd isotope systematics of Archaean granites of the Eastern Goldfields, Yilgarn Craton, Australia: Implications for crustal growth processes. *Precambrian Research*, 83, 109-132.

Chappell, B W, and Stephens, W E, 1988. Origin of infracrustal (I-type) granite magmas. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, 79: 71-86.

Collins, W J, 1993. Melting of Archaean sialic crust under high aH_2O conditions: genesis of 3300 Na-rich granitoids in the Mount Edgar Batholith, Pilbara block, Western Australia. *Precambrian Research*, 60, 151-174.

Davy, R, 1988. Geochemical patterns in granitoids of the Corunna Downs Batholith, Western Australia. *Geological Survey of Western Australia Professional Paper*, 23, 51-84.

THE RESTITE MODEL: A REVOLUTION IN PETROGENESIS?

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The restite model not only contends that many granites contain crystals of unmelted but magmatically equilibrated source material, or restite, but also that variations in the proportion of such restite, and melt, accounts for much of the variation in many granite suites.

The restite model had its origin in a study of what are now called I-type granites, in the Moonbi district of the New England Batholith of south-eastern Australia (Chappell, 1966). The concept was suggested, first, by the extraordinary linear trends of some elements and the lack of any curved trends among those granites. Also, the granites had textural features such as clusters of mafic minerals and uniform plagioclase cores that were interpreted as resulting from the incorporation of partly recrystallised source material. At that time, mafic enclaves were assigned an important role as a source of individual crystals of restite. These features could perhaps have been interpreted just as satisfactorily using a model of magma mingling, but such processes have never appealed to this author because of physical difficulties, and the discovery within a few years of S-type granites which clearly evolved in the same way, despite a lack of igneous enclaves. What may have been largely a prejudice against magma mingling has now been confirmed as realistic by more detailed studies of patterns of chemical variation (Chappell, 1996a) and by the fact that suites in the Bega Batholith do not change systematically in isotopic composition with changes in chemical composition (Chappell and McCulloch, 1990). It must also be noted that there are enclaves in S-type granites that others have regarded as igneous, but which Doone Wyborn has pointed out have striking compositional similarities with calcareous beds in the Ordovician sediments of the Lachlan Fold Belt, and which are probably lithic enclaves from such a source, but perhaps from older rocks.

Conceived in New England, the restite model grew to maturity in the Lachlan, where most of the more mafic I-type granites show similar distinguishing features, with the additional and striking supporting evidence from the mafic S-type granites. There have been three publications specifically on this subject, by White and Chappell (1977), Chappell *et al.* (1987), and Chappell and White (1991). A major fourth paper is in preparation (Chappell *et al.*, 1999). Among the Lachlan granites, powerful support for the restite model comes from the contrast in petrological and compositional features with suites that evolved through fractional crystallisation, such as Boggy Plain (Wyborn, 1983), and the inability of that other process to account for many of the compositional trends in both I- and S-type suites. The universal occurrence of age inheritance in zircon cores that are surrounded by rims yielding the magmatic age (e.g. Williams, 1995), in those suites for which on other grounds restite would be assigned an important role, has been a critical observation. This not only shows that the magmas were never *completely* molten, but also, the presence of those old zircons implies that zircon was always saturated in the melts involved in producing those suites, which is confirmed by the patterns of bulk rock Zr variation. Since those melts were always saturated in zircon, they could not have been at temperatures above the zircon saturation temperature of Watson and Harrison (1984) for any significant time. The calculated zircon saturation temperature for melts with compositions corresponding to the most mafic rocks of these suites are ~ 750 °C, very much lower than the temperatures that would have been required for material of that composition to have been completely or even largely molten. For the same reason, it is unlikely that the rocks are cumulates produced from melts of somewhat less mafic compositions, but that possibility can easily be ruled out on other grounds. These arguments imply that the melt involved in the production of these suites was both felsic, and at low temperature, and confirms that the more mafic rocks have that property because of the presence of crystals of entrained restite. Chappell *et al.* (1999) therefore distinguished between granites, both I- and S-type, which formed at low magmatic temperatures, and other I-type granites formed at high temperatures, such as the Boggy Plain Suite of Wyborn *et al.* (1987). Under that scenario, most granites of the Lachlan Fold Belt, and also the Moonbi Granites of New England, formed by partial melting of quartzofeldspathic rocks in the crust. In most cases, the melt compositions were close to those determined experimentally by Tuttle and Bowen (1958) at the lowest magmatic temperatures, and variation within the suite, except at very felsic compositions, is the result of fractionation of restite from melt. In some cases, the felsic melts evolved further by fractional crystallisation of quartz and feldspars, after separation of restite, to produce rocks with highly fractionated trace element abundances. Less often, the initial melting continued to higher temperatures, but the more mafic magmas when emplaced nevertheless contained crystals of restite, including zircon. In such cases, the more mafic compositions evolved through restite crystal fractionation, and the more felsic sometimes also by fractional crystallisation, e.g. in the S-type Koetong Suite (Chappell and White, 1998), again at times leading to extremes in trace element compositions.

The variation diagram for Zr in the S-type Bullenbalong Suite published by White and Chappell (1988) showed Zr contents increasing with decreasing total FeO contents (increasing SiO_2), with a sharp inflexion at close to 3.5% FeO (68% SiO_2), leading to progressively decreasing Zr abundances as the rocks became more felsic. Such a kink in Zr abundances is characteristic of rock series formed by fractional crystallisation, such as the Boggy Plain pluton (Wyborn, 1983) where Zr is not saturated in the early formed more mafic rocks, so that its abundance increases in the melt, including trapped inter-cumulus melt. The combination of falling temperatures and increasing Zr concentrations in the melt leads to saturation in that element, following which Zr abundances decrease in subsequently formed rocks. However, the variation within the Bullenbalong Suite cannot be accounted for in that way, because all mafic S-type granites that have been examined, including those of that suite, contain abundant age inheritance in the zircon crystals, which implies that the silicate melts involved in the production of that suite were always saturated in Zr. For that reason, the inflexion in Zr abundances cannot be due to the development of Zr saturation during fractional crystallisation and some other mechanism is required. It is proposed that the more mafic Bullenbalong granites have retained specific sedimentary source rock compositions without fractionation, and that the abundances of Zr and SiO_2 were positively correlated in those source rocks. Only the most SiO_2- and Zr-rich source rocks produced magmas in which the melt could and did fractionate from the restite, to produce the more felsic part of the variation in the suite, in which those two components are negatively correlated. In this model, the more mafic granites of the Bullenbalong Suite represent source sedimentary rocks that were partially melted to the magmatic stage, following which they moved upwards (to sometimes erupt) and solidified without any fractionation of melt from restite. This is a significant modification, but an enhancement, of the restite model. Some current data hint at a similar situation for more mafic I-type granites.

The restite model has not been without its critics, most notably Wall *et al.* (1987). Those authors proposed that it be left to *R*est *I*n *P*eace. Perhaps a more reasonable view, based on abundant field, petrographic, geochemical, experimental, and zircon age inheritance data, is that it represents a *R*evolution *I*n *P*etrogenesis. However, the significance of the restite model is not restricted to petrogenetic aspects, and there are wider implications, discussed in some detail by Chappell (1996b). It alleviates the problems of introducing large amounts of heat into the crust, since the requirement is for a partially molten magma rather than a complete melt, and at substantially lower temperatures. It has important implications for how the crust has been fractionated into a more mafic lower crust and granodioritic upper crust compositions, and has indeed been a factor in determining the composition of the exposed continental crust. However, probably the two most important implications are that it provides the opportunity to better estimate the composition of the source rocks in the deeper crust, and its implications for the production of mineral deposits. The first of those, means that many granites can be used as compositional probes of the deep crust, and its first use in that way was to relate compositional properties of granites to corresponding features in their source rocks, leading to the I- and S-types (Chappell and White, 1974, 1992). Later, an "I-S line" was recognised in the eastern Lachlan Fold Belt and correlated with an eastern limit of thick metasedimentary crust in that belt by White *et al.* (1976). Subsequently, Chappell *et al.* (1988) extended that principle to the whole of that belt in their proposition that the granite provinces that can be recognised, correspond with basement terranes. The implications of the restite model and the recognition of low-and high-temperature I-type granites by Chappell *et al.* (1999), for the formation of mineral deposits, are clear and obvious. To quote from that paper: "Because of both their higher temperatures, and a greater potential to undergo changes in composition, including an increase in the activity of H_2O, through the process of fractional crystallisation, the high-temperature granite types are more likely to be related to significant mineralisation. This is clearly seen in eastern Australia (Blevin and Chappell, 1992) where, for example, most of the Devonian- and Carboniferous-age I-type granites of the Lachlan Fold Belt, largely of low-temperature origin, are conspicuously lacking in associated mineralisation. The better understanding of these two granite types that we are now developing, along with better criteria to recognise them, should have important implications for mineral exploration."

REFERENCES

Blevin, P L, and Chappell, B W, 1992. The role of magma sources, oxidation states and fractionation in determining the granite metallogeny of eastern Australia. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 305-316.

Chappell, B W, 1966. Petrogenesis of the granites at Moonbi, New South Wales. PhD thesis, Australian National University, Canberra (*unpubl.*).

Chappell, B W, 1996a. Magma mixing and the production of compositional variation within granite suites: evidence from the granites of southeastern Australia. *Journal of Petrology* **37**, 449-470.

Chappell, B W, 1996b. Compositional variation within granite suites of the Lachlan Fold Belt: its causes and implications for the physical state of granite magma. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87**, 159-170.

Chappell, B W, and White, A J R, 1974. Two contrasting granite types. *Pacific Geology* **8**, 173-174.

Chappell, B W, and White, A J R, 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 1-26.

Chappell, B W, White, A J R, and Wyborn, D, 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* **28**, 1111-1138.

Chappell, B W, Bryant, C J, Wyborn, D, White, A J R, and Williams, I S, 1999. High- and low-temperature I-type granites. *Resource Geology* (in press).

Chappell, B W, and McCulloch, M T, 1990. Possible mixed source rocks in the Bega Batholith: constraints provided by combined chemical and isotopic studies. *Abstracts Geological Society of Australia* **27**, 17.

Chappell, B W, and White, A J R, 1991. Restite enclaves and the restite model. *In* Didier, J. and Barbarin, B. (eds), *Enclaves and Granite Petrology*, pp. 375-381. Elsevier, Amsterdam.

Chappell, B W, and White, A J R, 1998. Development of P-rich granites by sequential restite fractionation and fractional crystallisation: the Koetong Suite in the Lachlan Fold Belt. *Acta Universitatis Carolinae, Geologica* **42**, 23-27.

Chappell, B W, White, A J R, Blundy, J D, Williams, I S, Johnnies, W, and Wyborn, D, 1999. Crystal fractionation of entrained restite: its role in producing compositional variation in some granites and related volcanic rocks, and implications. (*in preparation*).

Chappell, B W, White, A J R, and Hine, R, 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **35**, 505-521.

Tuttle, O F, and Bowen, N L, 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. *The Geological Society of America Memoir* **74**.

Wall, V J, Clemens, J D, and Clarke, D B, 1987. Models for granitoid evolution and source compositions. *The Journal of Geology* **95**, 731-730.

Watson, E B, and Harrison, T M, 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters*, **64**, 295-304.

White, A J R, and Chappell, B W, 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* **43**, 7-22.

White, A J R, and Chappell, B W, 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

White, A J R, Williams, I S, and Chappell, B W, 1976. The Jindabyne Thrust and its tectonic, physiographic and petrogenetic significance. *Journal of the Geological Society of Australia* **23**, 105-112.

Williams, I S, 1995. Zircon analysis by ion microprobe: the case of the eastern Australian granites. *Leon T. Silver 70th Birthday Symposium and Celebration*, The California Institute of Technology, 27-31.

Wyborn, D, 1983. Fractionation processes in the Boggy Plain zoned pluton. PhD thesis, Australian National University, Canberra (*unpubl.*).

Wyborn, D, Turner, B S, and Chappell, B.W., 1987. The Boggy Plain Supersuite: a distinctive belt of I-type igneous rocks of potential economic significance in the Lachlan Fold Belt. *Australian Journal of Earth Science* **34**, 21-43.

NEW ANGLE ON SUBDUCTION ZONE MAGMAS: LASER ABLATION MICROANALYSIS AT ANU

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The Helex laser ablation microanalysis system, a ANU development jointly undertaken between the Department of Geology and Research School of Earth Sciences, is providing new opportunities to address a wide range of geochemical processes and problems, particularly in regard to the evolution and metallogeny of subduction zone magmas. The Helex system, based on precision laser micromachining technology using near vacuum ultraviolet (193nm) light, is able to vaporise and sample stoichiometrically virtually any material (aluminosilicate, sulfide, carbonate, oxide or metal) and to sweep the condensed particulates via a gas stream into an Ar plasma for analysis by emission spectroscopy (ICPES) or mass spectrometry (ICPMS). The Helex system can sample sites of any shape within the dimensions 400µm by 1mm and as small as 10µm, and has the capability to analyse any line profile or array pattern under computer controlled rastering. This inherent flexiblity affords an unrivalled range of bulk, site microsampling and mulitdimensional compositional profiling analytical tasks. Moreover, the superior sensitivity attained with the Helex system enables low and sub ppb level detection limits for virtually any element, even on very tiny spots (<50µm), with the simultaineous analysis of 20 to 30 elements requiring only 1 minute. Several outstanding examples where the Helex system has been applied to subduction zone magmas include:

MARIANA AND IZU-BONIN ARC ASH RECORDS

Measurement of a set of petrogenetic trace elements in microscopic basaltic to rhyolitic glass shards recovered as ash layers from ODP drilling sites outboard of the Mariana and Izu Bonin arcs has enabled Colleen Bryant and Richard Arculus to construct a complete spatial and temporal chronology of the development of these arc system since their inception in the Eocene. Distinctive breaks and subtle evolution in glass shard chemistry, that accompany the initiation, development and cessation of discrete intervals of back arc basin spreading, are providing a picture of the dynamics of subduction zone systems and enabling fundamental aspects of magma generation in subduction zones to be understood.

IN-SITU PGE, GOLD AND RHENIUM ANALYSIS

Ultratrace levels of Platinum group elements, Re and Au, are able to be analysed *in situ* using the Helex system. This capability has been used to establish the occurrence of anomallously high levels of many of these elements in basaltic glasses from subduction zones compared to other tectonic settings. In addition, the analysis of silicate and oxide phenocrysts, metal and sulfide phases, is enabling the emergence of a coherent picture of the behaviour of these elements in evolving magmatic systems.

TRACE ELEMENTS IN TRAPPED MELT AND FLUID INCLUSIONS

The spatial resolution and sensitivity of the Helex systems enables tiny glass, brine, or fluid inclusions trapped within host crystals to be analysed for trace lithophile, chalcophile and siderophile elements. In the case of glass inclusions in phenocryst phases, we are able to 'see into' the chemical inventories and behaviour of elements within magma reservoirs at depth unhindered by the unavoidable loss of a magmatic volatile phase and loss of metals that affect erupted magmas. To date, high levels of dissolved sulfur and certain ore forming metals are being documented in subduction zone magmas, and evidence is present for their systematic loss from these magma systems at depth. Further studies are being aimed at elucidating systematics in the behaviour and concentrations of these elements as magma system evolve across the range of compositions observed in subduction zones.

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PLUTONIC SUITE RECOGNITION IN THE BEGA AND MORUYA BATHOLITHS USING A MULTIVARIATE EXTENSION OF ENTROPY ANALYSIS OF THE CHEMICAL DATA BASE.

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One of the important aspects of granite suites is that they represent a range of rock types that are genetically connected rather than a group of near identical rocks. This makes the problem of computer-based suite recognition much more difficult than might be encountered subdividing a single group of rocks like basalts. For a statistical package to work it has to be able to ignore the very different bulk compositions of intermediate and felsic granitoids and "see" the subtle similarities that might indicate the relatedness of a particular group of diorites, granodiorites and adamellites. Although it may be useful to examine how the chemical data base can be subdivided statistically, there is no obvious reason why suites need to be able to be recognised/defined in this way and it is probable that as granitoid suites are groups of plutons, the chemical variation within a particular pluton may provide the most important control on suite definition.

In the Bega Batholith of the Lachlan Fold Belt the large chemical data base has allowed statistical methods to be used to test the distinctiveness of the component granitoid suites. Although this statistical approach has shown that cluster analysis using a restricted group of elements does distinguish the suites (Whitten and Chappell, 1984, Whitten *et al.* 1987), the use of the full complement of elements has been less successful .

A multivariate extension of entropy analysis used by Forrest and Clark (1989) in a sedimentology application has the advantage over some other statistic packages, of being able to treat the totality of the chemical data without imposing any of the customary limitations on the form of the data such as normality of distribution. The advantages of this method is discussed by Forrest and Clark (1989) and are reviewed in detail by Johnson and Semple (1983). In summary the method groups analyses with similar major and trace element profiles, where the profile is the exact shape of each distribution across all elements. Furthermore, unlike other grouping techniques, it minimises the amount of within-group variance by testing all possible groupings of observations; each level of grouping is entirely independent of any other.

To date our preliminary study has shown that subdividing the chemical data base into groups using this approach indicates that:

(a) Increasing the number of groups above 8 does little to decrease the entropy within groups; eight appears to be the optimal number of groups.

(b) The geographic distribution of most of the groups are north-south elongate; the well documented east to west variation is being recognised but these groups do not match exactly the recognised suites.

(c) One group that consists of samples from the southern part of the Bega Batholith has a subcircular outline.

(d) The removal of the twenty most silica-rich samples (initially expected to make the suite recognition clearer by removal of samples that may so strongly reflect the minimum melt composition and/or have unusual trace element values as a result of strong fractionation) was found to make little difference to the groupings.

The possibility exists that in granite subdivision, like chess playing, the computer programs will require a lot of refinement to become as clever at seeing the critical aspects of the problem as the masters.

REFERENCES

Forrest, J, and Clark, N R, 1989. Characterizing grain size distributions: evaluation of a new approach using a multivariate extension of entropy analysis. *Sedimentology*, **36**, 711-722.

Johnson, R J, and Semple, R K, 1983. *Classification using information statistics.* Geobooks, Norwich.

Whitten, E H T, and Chappell, B W, 1984. Suites within a granitoid batholith: a quantitative justification based on the Lachlan Fold Belt, SE Australia. *International Geological Congress, 27th, Moscow, Abstract vol. iv,* p 489.

Whitten, E T H, Bornhorst, T J, Li, G, Hicks, D L, and Beckworth, J P, 1987. Suites, subdivision of batholiths and igneous-rock classification: geological and mathematical conceptualization. *American Journal of Science,* **287**, 332-352.

HOW THE MANTLE MAKES GRANITES

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An extensive database on the composition of the subcontinental lithospheric mantle (SCLM) demonstrates secular evolution in the mean composition of SCLM formed at different times during Earth's history. This evolution involves a decrease through time in all measures of depletion, such as Al, Ca, mg#, and Fe/Al. Archean SCLM is highly depleted, and Proterozoic SCLM less so, while Cenozoic SCLM, exemplified by Zabargad spinel peridotites and by garnet peridotite xenoliths from Phanerozoic terrains, is only mildly depleted relative to Primitive Mantle.

Average mineral compositions for each age group have been used to calculate average modes and densities. Archean SCLM is 2.5% less dense than the asthenosphere; for Phanerozoic mantle the difference is <1%. Typical geotherms, thermal expansion coefficients and bulk moduli have been used to calculate density variation with depth for typical Archean, Proterozoic and Phanerozoic SCLM. The entire section of Archean SCLM is buoyant relative to the underlying asthenosphere. For Proterozoic and Phanerozoic mantles, density decreases with depth due to their higher geotherms, but a minimum thickness of ca 30 and 60km respectively must be reached before each section becomes buoyant. This effect explains the thickness and apparent longevity of existing Archean (and thick Proterozoic) lithosphere.

Mantle-derived xenoliths from three areas with extensive Phanerozoic late- to post-orogenic granitic magmatism (East Central Asia Orogenic Belt (ECAOB); SE China; E. Australia) show striking similarities. All show a SCLM column <100 km thick, with a high advective geotherm. In most localities the SCLM consists of spinel peridotite from the crust-mantle boundary to depths of 45-60 km, with garnet ± spinel peridotites at greater depth. Most of the SCLM sections sampled here show chemical stratification. Garnet peridotites generally show low degrees of depletion (?5% partial melting), as reflected in high abundances of cpx+ gnt, and CaO and $Al2O3$ contents of 2.5-4 wt. %. Most of the spinel peridotites are similarly fertile, but some show higher degrees of depletion, followed by metasomatic enrichment in LREE and incompatible elements such as U, Th, Sr and Zr. Some of these more depleted spinel lherzolites may represent older lithosphere, especially in the ECAOB and SE China areas. The accretion history of these areas, with the closing of ocean basins, is not reflected in the xenolith suites; none is depleted enough to represent typical oceanic or island-arc mantle. The present SCLM structure beneath the areas sampled is interpreted as consisting of (1) shallow thin remnants of older continental or oceanic lithospheric mantle mixed with younger asthenospheric material, and (2) deeper underplated "asthenospheric" material, probably modified by minor further melting during upwelling.

Density modelling shows that cool oceanic or sub-arc mantle is not gravitationally stable if <60 km thick; it can be subducted, or delaminated under compressive stress. Detachment of this lithosphere might be expected during continental accretion, and will allow upwelling of hotter asthenospheric material, providing a large, regionally distributed heat source. If the geotherm during this process approximates the Cenozoic xenolith-derived geotherm (probably a minimum estimate), temperatures will reach 900-1000 °C at the crust-mantle boundary and 700-800 °C in the middle crust, causing massive melting, granitoid production and basification in the lower crust. This mechanism could explain the large volumes of late/post-tectonic granitoids intruded across regions such as the ECAOB and SE China, and perhaps in eastern Australia.

Archean and Proterozoic SCLM is essentially impossible to "delaminate" due to its buoyant, depleted nature; "thermal erosion" can only increase its buoyancy. However, buoyant SCLM roots may be broken apart and dispersed by regional rifting, as shown by recent seismic tomography studies in China, to produce a SCLM of mixed provenance. This mechanism allows the upwelling of asthenospheric material to shallow depths, and can raise geotherms to the level required to produce melting in the lower to middle crust. This mechanism currently is operating over an area at least 600 x 1200 km in the eastern Sino-Korean Craton, and might serve as a model for widespread Proterozoic intraplate granitoid magmatism in central and northern Australia.

CONTINENTAL FLOOD BASALTS AND THE SUBCONTINENTAL MANTLE

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It has been proposed that large plumes of mantle material rising from great depths are responsible for vast outpourings of magma, both in continental and oceanic environments. This has been supported by geophysical modelling in which the temperatures of these plumes and their geodynamic properties predict high volumes of melt production as these impinge on the Earth's crust. However, such models are at odds with geochemical data for basaltic magmas from oceanic and continental regions where it is clear that materials of different composition provide the sources for these two groups of flood basalt magmatism.

In the case of at least the Mesozoic continental flood basalts, two broad chemical groups are recognised, and these are referred to as 'high Ti' and 'low Ti' respectively. In detail, the absolute concentration of Ti is unimportant, and it is the Ti content relative to Zr and Y which characterises each group. In the low Ti continental flood basalts, a significant depletion in Ti exists relative to Zr and Y, and this generates a negative anomaly in the mantle-normalised trace element patterns of these rocks. High and low Ti rocks occupy distinct geographic provinces and would appear to be derived from separate subcontinental mantle sources.

The petrogenesis of low Ti continental flood basalts remains particularly controversial. While the mineralogy is relatively simple (clinopyroxene+plagioclase±olivine±orthopyroxene±pigeonite) and the rocks are clearly tholeiitic, the major element compositions are unusual compared with their oceanic counterparts. Specifically, Si tends to be high and Na, Fe, Ti and P are generally low in the continental examples. More striking is the difference in key incompatible trace element and isotope features between the low Ti continental flood basalts and oceanic tholeiites. Despite their 'basaltic' mineralogy, the former display incompatible trace element features more reminiscent of rocks from the upper continental crust (e.g., granites and sediments) than the mantle. As incompatible elements, it is not surprising then that the Sr, Nd and Pb isotope compositions also reflect similar 'crustal' signatures.

In order to reconcile the 'upper crustal features' of otherwise 'basaltic' rocks, two broad groups of models have emerged. In the first, it is proposed that basaltic magmas interact with materials from the continental crust to generate the characteristics observed. In other words, the major elements are effectively derived from the mantle source, with the incompatible elements (and related isotope features) reflecting a separate component in the continental crust. These types of models appear to be compatible with geophysical models for 'plume-lithosphere interaction' whereby heat and magma extracted from a rising mantle plume would facilitate the incorporation of crustal material required to generate a flood basalt magma.

In contrast, the second group of models propose that all features are inherited from the mantle source at the time of partial melting. This implies that the mantle source must be somehow modified beneath continents, and that, as a consequence, the major, trace element, and isotopic features of the magmas are coupled (i.e., have a shared origin and history once the melt is formed). Such models are less compatible with a plume origin for low Ti flood basalts, since there is no evidence to suggest that these mantle reservoirs ever carry upper crustal trace element characteristics. In short, if plumes are involved in these models, they are viewed as a useful source of heat (triggering magmatism) rather than material, and do not represent the source of the magma. In some models the proposed mantle source lies within the subcontinental lithospheric mantle owing to the depletion of certain elements in the magmas.

There is no question that low Ti continental flood basalts preserve a clear record for some form of mantle-crust interaction in their magmagenesis; at issue is whether this takes place within the crust or mantle. To unravel the details of such interaction, it is useful to investigate the most extreme compositions within this group. Of all studied low Ti continental flood basalts, the Ferrar Province (including Antarctica, Australia, New Zealand) includes rocks with highest Si and lowest Fe, Ti, Na, P at a given Mg#, while recording the most 'crustal'-incompatible trace element and isotope signatures.

An important feature of the incompatible trace element compositions (as typified by chilled margin rocks of Tasmanian dolerite intrusions for example) is that the overall concentration of such elements is broadly similar to oceanic tholeiites, but with significant enrichments and depletions in key elements. Put simply, the saw-toothed mantle normalised trace element patterns show remarkable similarities with upper continental crust, but translated to more basaltic concentrations.

Such observations make it difficult to envisage a means of mixing basalt magmas with crustal materials, as the concentrations of the observed magmas simply do not plot between any two such endmembers. Indeed mixing calculations (with or without associated fractional crystallisation) would require at least 25-30% assimilation of upper crust, by a most unusual 'basalt' (with selected features of picrites *and* boninites, and with certain trace elements restricted to concentrations more typical of peridotites) in order to match the trace element features of the Ferrar magmas. Using more typical basalt compositions, the crustal assimilant would be required to have negative concentrations of key trace elements. Such problems are exacerbated when the Sr, Nd and Pb isotope compositions of the two proposed endmembers are also considered. While perhaps physically a more attractive solution, crustal-level assimilation processes are difficult to reconcile with the geochemical data of the Ferrar low Ti continental flood basalts.

The greatest difficulty in achieving esssentially basaltic magmas, with upper crustal trace element and isotope characteristics is overcome if material from the continental crust is introduced into a depleted mantle source region. The incompatible trace element concentrations of mantle peridotite are approximately an order of magnitude lower than that of their tholeiitic partial melts. Clearly, only a trivial proportion of upper crustal material (less than 3%) would be required to completely overprint the incompatible element and Sr, Nd, Pb isotope compositions of this material. During subsequent partial melting, the melts generated would inherit upper crustal features from their modified mantle source. Such models are less attractive as a number of new questions arise: how is depleted and re-enriched mantle melted?, do we need to store such materials and if so, where?, why don't we see evidence for such modified mantle in our xenolith suites?, if plumes are involved, why do we not see lavas associated with plumes in these provinces?

Notwithstanding such issues, the fact remains that these rocks exist, and when we search for evidence for crustal-level assimilation, it is lacking. Examination of the most primitive member of the Ferrar suite (a rare olivine-bearing tholeiite) reveals that the upper crustal features are already present at the earliest stages of evolution. In the case of the Kirkpatrick Basalts (Antarctica) where AFC processes have been proposed, the models must use starting compositions which already bear upper crustal features. Additional evidence in support of mantle modification models is provided by oxygen isotope data. Whereas 25-30% assimilation of upper crust would require a significant shift in the basalt values towards higher $\delta^{18}O$, the effects of introducing small percentages of crust into the mantle source region would be negligible. This is because, unlike Sr, Nd and Pb which may be dominated by a single endmember, O is a major element, comprising approximately 50% of both crust and mantle source rocks. The values preserved in fresh chilled margin rocks (e.g., Tasmania) are close to mantle values (~5.5‰) which can only be explained by restricting the involvement of upper crustal material to a small volume.

A final test is provided by the application of the Re-Os isotope system to the Ferrar continental flood basalts. Os is strongly enriched in the mantle relative to the crust, however basaltic magmas may contain even less Os than is found in granite and would therefore be prone to the same problems involving crustal-level contamination as experienced by the Sr, Nd and Pb isotopic systems. For example, 10% bulk assimilation of material by a basalt *en route* through the continental crust, could produce a mixture in which 20% of the Os is 'granitic'. Clearly, if the crustal material is radiogenic, this will influence the Os isotopic composition of the contaminated basaltic magma. Importantly, (and unlike the case for Sr, Nd and Pb) the same does not hold if the contamination occurs in the mantle source region owing to the higher relative abundance of Os in the mantle compared with crustal rocks. Simple mass-balance calculations indicate that the introduction of 3% sediment (0.06 ppb) into a mantle peridotite source, would produce a contaminated source in which less than 0.04% of the Os was derived from the sediment. Thus it would be possible to distinguish between crustal-level contamination processes, and those operating within the sub-continental mantle. This is enormously useful, and may be the only indisputable way in which the modification and subsequent large-scale remobilisation of the sub-continental mantle to generate low Ti continental flood basalts might successfully be demonstrated.

REDOX STATUS OF THE PHANEROZOIC GRANITES IN THE CIRCUM-PACIFIC OROGENIC BELTS

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Recent measurement on magnetic susceptibility and the study of opaque minerals of granitoids (Ishihara, 1979; Tainosho *et al.*, 1988; Whalen and Chappell 1988; Gastil *et al.*, 1990; Bateman *et al.*, 1991), have clarified the regional distribution of the oxidized (magnetite-series) and reduced (ilmenite-series) types of granitoids in the Circum-Pacific orogenic belts. The distribution patterns and their geneses are briefly reviewed here, based on regional identification of the two series of granitoids.

Jurassic-Quaternary granitic rocks in the Japanese Islands, occur inseveral narrow (80-100 km) belts in different tectonic units. A paired belt of fore-arc ilmenite-series (Sanyo-Ryoke Belt) and back-arc magnetite-series (Sanin Belt) granitoids are a basic pattern of the largest granitic unit of the late Cretaceous-Paleogene Southwest Inner Zone batholith. The whole batholith is calculated to consist of 67% ilmenite series and 33% magnetite-series granitoids, based on the measurement of magnetic susceptibility (n=2,030). The paired belt is also seen in the Miocene-Quaternary magmatic region.

On the contrary to the Japanese Islands situation, granitic magmatism occurred in much wider portions of continental regions of Far East Asia (300-500 km). Jurassic-Paleogene granitoids are known in the Sikhote Alin and Okhotsk regions of the Russian Far East. Here ilmenite-series rocks are predominant in the Mesozoic granitic terranes, and magnetite-series rocks prevail only during the final, late Cretaceous-Paleogene stage, of magmatic activity. Thus, over the whole region, ilmenite-series granitoids appear to be dominant, whereas magnetite-series rocks are limited to the coastal area.

In the Jurassic-Cretaceous granitoids of the southern Korean Peninsula, the magnetic susceptibility tends to increase from the interior of the peninsula to the Gyeongsang Basin of the southeastern corner. In southern China, the Early Yanshanian Jurassic granitoids consist of 74% ilmenite series and the Late Yanshanian Cretaceous rocks of 68%. Late Yanshanian granitoids of the Fujian coastal volcano-plutonic belt, which are the southwestern extension of the Gyeongsang Basin granitoids in South Korea, are strongly magnetic; oxygen fugacity of the granitoids must have been high because of hematitization reported in the rock-forming magnetite of the granitoids. Magnetite-series granitoids occur further inland along the Yangtze fold belt. These granitoids are alkaline and thus were likely to have a high oxygen fugacity.

The regional pattern of the coastal and back-arc magnetite-series granitoids facing the marginal basins in the western Pacific led Ishihara (1981) to propose a genetic model related to the back-arc spreading. In the subduction-related continental margin and island-arc environment, mantle-derived magmas that are oxidized with high Fe^{3+}/Fe^{2+} ratios, ascended without any crustal contamination in the back-arc basins due to the extensional tectonic setting of the marginal basins. In contrast, along the compressional tectonic setting of the arc front, the magmas may have been modified while passing through the continental crust, by assimilation of crustal material, which contain various quantities of C-bearing sediments. Thus, the reduced ilmenite-series magmas were formed.

In the Caledonian granitoids of the Lachlan Fold Belt, southeastern Australia, magnetic susceptibility measurement by Tainosho *et al.* (1988) indicates that all the S type and 45% of the I type granitoids belong to the ilmenite-series, whereas the A types belong to the ilmenite series. Overall, the measurements imply 67% ilmenite-series and 33 % magnetite-series rocks at surface. Magnetic susceptibilities of the magnetite-bearing I-type granitoids in Australia are lower than the average values of typical magnetite-series granitoids of the Sanin Belt in Japan. The Lachlan granitoids seem to be more reduced than the Japanese granitoids.

In contrast to the western Pacific rim, the Cordilleran granitoids of North and South America are characterized by narrow granitic belts with different distribution patterns. A magnetic study in northern Chile indicates that the late Paleozoic granitoids are composed of both magnetite- and ilmenite-series, but the Jurassic-Paleogene granitoids are strongly magnetite bearing (98% magnetite series). These rocks have low magnetic susceptibilities in the west and high values in the east. In the Peru-Bolivian transect, the coastal batholith is I-type magnetite series but the inner Sn-mineralized granitic belt is I-type ilmenite series.

In the Peninsular Range batholith, magnetic susceptibility of these plutonic rocks are high in the west and low in the east. Accordingly, Gastil *et al.* (1990) drew the magnetite-ilmenite boundary in the middle of the batholith where the coastal gabbroids and tonalites are magnetite bearing and meta-aluminous, and the eastern granitoids are magnetite free and peraluminous. The regional variations are also shown in the initial Sr ratio of 0.7025 in the west and 0.708 in the east, and oxygen isotopic ratio of 6.0 permil $\delta^{18}O$ to the west and 13.0 permil to the east (Silver *et al.*, 1979). These isotopic data indicate that the plutonic rocks originated from deep mafic material and supracrustal sedimentary rocks plus some hydrothermally altered oceanic crust. Granitic plutons located east of the main batholith again revert to magnetite series. Gastil *et al.* (1990) proposed a depth-dependent model for the generation of the three zones of magmas along a subduction plane.

In the Sierra Nevada batholith of California, magnetic susceptibilities of the granitoids are generally low in the western foothills, and high to the east. As a whole, the magnetite-/ilmenite-series ratio is 73/27. In the western foothill area, ilmenite series are common around the Coarsegold roof pendant. Based on $\delta^{34}S_{CDT}$ values of the whole rock sulfur, Ishihara and Sasaki (1989) suggested that granitic magmas of the Sierra Nevada batholith were essentially I-type magnetite-series, and the ilmenite series in the western foothills were formed by local reduction caused by reduced species, such as of carbon and sulfur assimilated from the wall rocks. Bateman *et al.* (1991) argued that, in the N-S transect work of the Coarsegold roof pendant, the initial Sr ratios do not correlate with the magnetic susceptibility values, and they proposed an alternative, deep-seated reduced source of the ilmenite-series granitoids.

Available data indicate that the regional distribution patterns of the magnetite- and ilmenite-series granitoids differ on both sides of the Pacific Ocean. Magnetite-series granitoids tend to occur along the continental margin of the western Pacific, but ilmenite-series rocks may prevail in the Cordilleran continental margin. These regional patterns reflect the intrinsic redox state of the granitic magmas; several models have been proposed for geneses of the differing redox state. The redox-status of Circum-Pacific granitoids is still poorly known in many other regions, and we need further field studies to improve our understanding of the two series of granitoids and also genetic examination of the granitic magmatism.

REFERENCES

Bateman, P C, Dodge, F C W, and Kistler, R W , 1991. Magnetic susceptibility and relation to $^{87}Sr/^{86}Sr$ for granitoids of the central Sierra Nevada, California. *Journal of Geophysical Research, B, Solid Earth and Planets* **98**, 19555-19568.

Gastil, G, Diamond, J L, Knaack, C, Walawender, M J, Marshall, M, Boyles, C, Chadwick, B, and Erskine, B, 1990. The problem of the magnetite/ilmenite boundary in Southern and Baja California. In: Anderson, J L, (ed.), The nature and origin of Cordilleran magmatism. *Geological Society of America, Memoir* **174**, 1-18.

Ishihara, S, 1979. Lateral variation of magnetic susceptibility of the Japanese Granitoids. *Journal of the Geological Society of Japan* **85**,509-523.

Ishihara, S, 1981. The granitoid series and mineralisation. *Economic Geology, 75th Anniversary Volume,* pp. 1905-1980.

Ishihara, S, and Sasaki, A, 1989. Sulfur isotopic ratios of the magnetite series and ilmenite-series granitoids of the Sierra Nevada Batholith; a reconnaissance study. *Geology* **17**, 788-791.

Silver, L T, Taylor, H P, and Chappell, B W, 1979. Some petrological, geochemical and geochronological observations of the Peninsular Ranges Batholith near the international border of the U.S.A. and Mexico. In: Abbott, P L and Todd, V R (eds), *Geological Society of America 1979 Guidebook*, pp. 83-110.

Tainosho, Y, White A J R, Chen, Y, and Wormald, R, 1988. Regional variation of magnetic susceptibility of the Lachlan Fold Belt Granitoids, southeastern Australia. *Journal of the Geological Society of Japan*, **94**, 657-668.

Whalen, J B, and Chappell, B W, 1988. Opaque mineralogy and mafic mineral chemistry of I- and S-type granites of the Lachlan Fold Belt, southeast Australia. *American Mineralogist* **73**, 281-296.

PLAGIOCLASE: A PROBLEMATIC PHASE IN GRANITE PRODUCING DEHYDRATION MELTING PROCESSES.

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The upper continental crust is enriched and the lower depleted in granite components. It is assumed that this is due to formation of partial melts in the lower crust, segregation of these melts and their ascent to higher levels.

The most important melting processes producing granitic partial melts at high grade metamorphic conditions are dehydration melting of amphibolites and tonalites. In both cases plagioclase is present in the parent rocks as well as in the reaction products. Dry melting of plagioclase is known to be very sluggish. It seems to be responsible for the inconsistencies and lack of precision of data obtained so far in experimental investigation of dehydration melting of amphibolites and tonalites. In order to elucidate the role of plagioclase in dehydration melting of plagioclase-bearing assemblages, melting of a plagioclase-hornblende mixture approaching the composition of an Archean amphibolite has been investigated at 8 and 12 kbar at 1000°C. In addition to these investigations experimental results obtained in kinetic studies of plagioclase melting (dry at 1 atm, H_2O-saturated at 5 kbar and in the tonalite system at 2 kbar) will be discussed.

The results of the kinetic studies in the various systems indicate that melting of plagioclase-bearing assemblages is very slow under dry conditions. The reaction rates and approach to equilibrium compositions is not controlled by chemical diffusion within the plagioclase, but by dissolution and recrystallization processes occurring at the grain boundaries of the reacting phases. Addition of components like H_2O and Al_2O_3 may increase the reaction rates.

The starting mixture of the first experiments on dehydration melting of amphibolites consisted of 65 wt% hornblende and 35 wt% plagioclase (An60). The grain size of these minerals was ≤ 10 µm. Back-scattered electron images of the products of time dependant runs show that even after a run duration of 36 days the plagioclase still contains unreacted cores. The reaction depth in plagioclase is only 2-3 µm after 36 days, similar to that observed previously after 10 days.

The grain size in the second set of experiments was ≤ 5 µm. In these experiments complete reaction was observed after 10 days. The following (near equilibrium ?) compositions were obtained for 8 and 12 kbar:

	8 kbar	*12 kbar*
% Garnet	-	32,2
% Clinopyroxene	29,3	34,2
% Orthopyroxene	9,7	-
% Plagioclase	32,3 (An_{49})	9,2 (An_{74})
% Hornblende	4,3	-
% Magnetite	5,8	-
% Melt	18,6	24,3
% Qz/Ab/An (melt)	29,2 / 47,0 / 33,8	4,8 / 62,0 / 33,2
% H2O in melt	6,1	5,1
a H2O in system	~ 0,35	~0,2
Viscosity of melt (poise)	~ 10^3	10^3 - 10^4

The composition of the minerals are also given and the REE pattern expected in the partial melts are calculated for an Archaean tholeiite as parent rock.

The new data suggest that magmas from which Archaean grey gneisses were formed, should have originated within the stability field of garnet at temperatures below 1000°C (lower than hitherto assumed).

INTEGRATED MODELING OF CRUSTAL DYNAMICS AND THERMAL EVOLUTION: APPLICATION TO THE EMPLACEMENT OF GRANITES.

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A new finite element modeling code allows us to study the thermal and mechanical evolution of the crust during the large-strain deformation associated with major tectonic upheavals. The major difficulty which we address is the need to follow faithfully the history of deformation in a system where some regions are actively convecting while other regions remain nearly stagnant. We describe a method which easily handles this situation by tracking a Lagrangian frame of reference through a standard Eulerian (fixed) grid. Our first example demonstrates a large-scale application: the thermomechanical evolution of a continent in the convecting mantle. Our second example is a smaller-scale model of a >>viscous (melted) mass of rock intruding a viscous-brittle cold crust. We then consider the application of this line of modeling to the process of granite emplacement with the expectation of vigorous discussion to follow.

THE PROCESSES CONTROLLING THE GEOCHEMISTRY OF ANDESITC MAGMAS IN NEW ZEALAND VOLCANOES AND THEIR RELEVANCE TO I-TYPE GRANITIC SUITES

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Petrological research concerned with andesitic volcanism is seldom linked with work on I-type granite complexes and yet at least some intrusive complexes must represent intracrustal magmatic systems that at one time underlay volcanic arcs. We report here some of the outcomes of a study of active andesitic volcanoes in the North Island of New Zealand and seek to integrate this information with data we have obtained for a Permian-Triassic aged intrusive complex in the South Island of New Zealand.

The largest, active, andesitic volcano in New Zealand is Ruapehu. At 2797 m it is also the highest mountain in the North Island. It has been active over at least 250 ka years, with the most recent eruption occurring during the period September to June 1996. The magmatic history of the volcano is preserved in laharic deposits and tephra units making up an extensive ring plain (Donaghue *et al.*, 1995) and in lava flow sequences of a complex central cone (Hackett, 1985). Ruapehu eruptives show a change with time to progressively more potassic compositions. The isotopic compositions also show temporal changes, and this is interpreted to reflect an increasing involvement of crustal material. With time Ruapehu magmas have become more evolved and more variable in terms of overall geochemistry and isotopic compositions. Collectively, data for samples from the volcano show a rough correlation between $^{87}Sr/^{86}Sr$ isotopic ratios and SiO_2 abundance and this has been interpreted (eg. Graham and Hackett, 1987) to reflect assimilation of crustal material, accompanied by crystal fractionation – assimilation crystal fractionation or AFC.

Detailed mapping of lava flows on Ruapehu has defined complex stratigraphic sequences and geochemical data have been collected to examine the fine scale petrological variation occurring within these. A 400m thick section of flows is exposed along the upper Whangaehu gorge on east Ruapehu and, within this section several lava flow sequences each containing three or four conformable flows have been distinguished. Geochemical variation within these sequences shows an overall cyclic pattern from relatively low SiO_2 contents to higher values with time and, although more variable, strontium isotopic compositions tend to show a similar pattern. The data are consistent with a model whereby magmas evolve within and erupt through a system of dykes probably located a few kilometres below the volcano. Eruption of discrete flow packages is possibly associated with recharge of dykes with fresh magma. Variation within the packages probably reflects crystal fractionation and mixing between fresh, recharging magma and magma remaining in the dyke system from previous recharge/fractionation events. Recharging magma batches vary considerably in composition, are all geochemically evolved, and show evidence for interaction with crust. They probably evolve in a deep magma reservoir located within the lower or middle crust.

Intrusive rocks, ranging in composition from ultramafic cumulates through gabbros and quartz diorites to granites, are exposed along the Southland coast at the southern end of the Longwood Ranges, in the south of New Zealand's South Island (Price and Sinton, 1978). All rocks show the trace element characteristics typical of subduction-related magmas and they are believed to represent the remnants of a Permian- Triassic volcanic arc (Kimborough *et al.*, 1994). Dykes are abundant within the complex and many of these are composite with compositions ranging from dolerite through andesite to dacite. Within some dykes, pillow like mafic material is contained within an envelope of more felsic rock and the margins of the pillows commonly show what appear to be chilled margins. Intermediate compositions within these dykes have compositions consistent with a derivation by mixing between mafic and felsic components. Dykes of this type could represent the feeder conduits for andesitic volcanoes that once overlay the intrusive complex. The felsic component in the dykes could represent either a residual evolved magma left from an earlier recharge event or melt derived by anatexis of the host quartz diorite

Dioritic rocks contain mafic enclaves in abundance and these are most common in complex zones marking the boundaries with gabbroic rocks. Enclaves of this type are commonly argued to represent mafic magma blobs that have mingled or mixed with the host (eg. Didier, 1973; Vernon *et al.*, 1988). Enclaves from the Longwoods quartz diorites have very distinctive and uniform compositions. They are enriched in rare earth elements (REE) relative to their hosts and the chondrite normalised REE patterns are characterised by depletion of the light relative to intermediate REE. They all show distinctive Eu depletions and they are all relatively depleted in Ni compared to other rocks with similar SiO_2 contents. They appear to be derived by crystal fractionation from magmas represented by the gabbroic rocks of the complex and they were probably incorporated when quartz diorite magmas were intruded into and disrupted evolving basaltic magma chambers. If the quartz diorites are mixed magmas, then the enclaves cannot represent the mafic component of this mixing trajectory.

REFERENCES

Didier, J, 1973. Granites and their enclaves: The bearing of enclaves on the origin of granites. *Developments in Petrology* **3**, 393 pages.

Donoghue, S L, Neall, V E, and Palmer, A S, 1995. Stratigraphy and chronology of late Quaternary andesitic tephra deposits, Tongariro Volcanic Centre, New Zealand. *Journal of the Royal Society of New Zealand* **25**, 115-206.

Graham, I J, and Hackett, W R, 1987. Petrology of calc-alkaline lavas from Ruapehu Volcano and related vents, Taupo Volcanic Zone, New Zealand. *Journal of Petrology* **28**, 531-567.

Hackett, W R, 1985. *Geology and petrology of Ruapehu Volcano and related vents.* Unpublished PhD Thesis, Victoria University of Wellington, New Zealand.

Kimborough, D L, Tulloch, A J, Coombs, D S, Landis, C A, Johnston, M R, and Mattinson, J M, 1994. Uranium-lead zircon ages from the Median tectonic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics* **37**, 393-419.

Price, R C, and Sinton, J M, 1978. Geochemical variations in a suite of granitoids and gabbros from Southland, New Zealand. *Contributions to Petrology and Geochemistry* **67**, 267-278.

Vernon, R H, Etheridge, M E, and Wall, V J, 1988. Shape and microstructure of microgranitoid enclaves: indicators of magma mingling and flow. *Lithos* **22**, 1-11.

MINGLING AND MIXING OF BASALTIC AND GRANITIC MAGMAS IN THE VINALHAVEN PLUTON, MAINE: A CONTRIBUTION TO THE COMPOSITIONAL VARIATION IN GRANITE CONTROVERSY

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The Vinalhaven pluton, in the Coastal Maine Magmatic Province, is a small (128 km^2) bi-modal pluton that displays abundant evidence of mingling and mixing of coeval granitic and basaltic magmas. There are two granite units, one coarse-grained and the other fine-grained. Both granites are uniform in composition, and differ only slightly in bulk composition. The fine-grained unit is probably the slightly younger of the two. On the southern and eastern sides of the pluton are two gabbroic bodies that are indistinguishable in composition. Associated with the gabbros are composite zones (net-vein complex) consisting of chilled basaltic pillows in a granitic matrix. In many places the gabbro is also invaded by composite dikes consisting of basalt pillows in a granite matrix. The Vinalhaven pluton is an outstanding example of a silicic magma body that has been invaded by basaltic magma which has ponded on the crystal -mush floor of the granitic magma chamber. Evidence for this interpretation comes from the observation of a chilled base of the gabbroic units resting on homogeneous granite, and from pipes of granite that pass upwards into the gabbro from the underlying granite. These pipes result from gravitational instability as heat from the invading basaltic layer melts the underlying granitic mush to produce a less-dense granitic mush that rises through the overlying basaltic magma. The composite pillow-zones may have originated in one of two ways. Either they are pillow deltas on the margins of the basaltic flows, or they reflect the localized disruption of the basaltic flows by concentrated invasion of the granitic pipes. I favor the second interpretation because the composite zones tend to occur as relatively narrow, distinct zones or bands between homogeneous massive gabbro.

Although there is clear evidence for extensive mingling between coeval granitic and basaltic magmas, extensive mixing or hybridization was minimal. There are no mapable units of intermediate rocks within the pluton. Despite extensive sampling looking for intermediate hybrid compositions, the data are distinctly bi-modal. There are two types of intermediate compositions: pillows and gabbros that have been slightly modified by interaction with the granitic magma, but still retain their distinct identity; and granitic matrix between the pillows that ranges in composition from the coarse granite to a granite that has been modified slightly by a mafic component. It is particularly noteworthy that this mafic component does not correspond in composition with the pillow compositions, or with the chilled margins of the gabbro, which are identical. Instead, the compositional trends for the granitic matrix are towards an evolved basaltic composition with about 3-4% MgO. Such compositions can be produced by about 60-70 percent fractionation of the parental pillow composition. These observations are consistent with fluid dynamic considerations which suggest that, because of viscosity contrasts, mixing of granitic and basaltic magmas are unlikely, but mixing between granite and evolved basaltic compositions are permissible. Thus, as intimate mingling occurs, mixing and hybridization does not take place, unless evolved interstitial basaltic melt leaks out of a rapidly cooling and crystallizing pillow.

The importance of this study is that, despite overwhelming evidence for the invasion of a silicic magma chamber by basaltic magma and the extensive co-mingling between the two magmas, mixing or hybridization between the two was minimal. Furthermore, the mixing trends that were produced were not towards the composition of the invading basaltic magma, but towards an evolved derivative of that magma. This would seem to suggest that the co-linear trends, so characteristic of granitic series in large granite batholiths, are not the products of magma mixing between granitic and basaltic magmas.

USE OF XRF IN THE STUDY OF HAWAIIAN VOLCANIC ROCKS

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Precise XRF major and trace element data have proved extremely useful for understanding magmatic processes in Hawaiian volcanic rocks, particularly those erupted on the tholeiitic shield volcanoes Mauna Loa and Kilauea. Previous studies of Mauna Loa lavas based on gravimetric analyses, impressed by the uniform composition of historical and young prehistoric lavas, concluded that these lavas were erupted from a very large magma reservoir of constant composition. More recent work on the historical lavas has shown small but significant, systematic changes in composition with time that are closely related to magma supply rates. These changes are interpreted as having resulted from mixing of two distinct parental magmas, one enriched and the other depleted in incompatible elements, in a small continuously replenished magma reservoir. The supply of the depleted parental magma is greatest when magma supply rates are high, whereas the enriched parental magma dominates the magmatic system during periods of low magma supply.

Both major and trace elements have proved to be effective discriminants between adjacent shield volcanoes. This has been a useful tool in geological mapping the boundary between Kilauea and Mauna Loa volcanoes, and in recognizing the transition from Mauna Loa lavas to those of Mauna Kea in the recent pilot drill hole of the Hawaiian Scientific Drilling Project. Of a more controversial nature was the discovery that Mauna Loa-like lavas were erupted on Kilauea volcano between about 2100 and 400 years ago. Field work showed that these were not Mauna Loa lavas that had simply overrun the Kilauea shield. There are two possible explanations of these observations. Either the mantle source for Kilauea lavas has changed rapidly over a very short period of time, or magma from Mauna Loa volcano has invaded Kilauea's magmatic plumbing system. I favor the later interpretation for several reasons. First, this appears to have been a very unique event; secondly, the Mauna Loa-like lavas are restricted to the summit region and are absent from Kilauea's lower rift zone, and, thirdly, these lavas have all the compositional characteristics of magmas that have been processed in Mauna Loa's continuously replenished magma reservoir.

The most effective discriminants between Hawaiian tholeiites are incompatible trace element ratios involving Nb (e.g. Zr/Nb, K/Nb, Sr/Nb, La/Nb and Nb/Y) because these ratios correlate with isotopic ratios such as $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ and therefore reflect differences in mantle plume source compositions. Use of these X/Nb ratios has shown that the plume sources for Kilauea and Mauna Kea volcanoes have remained relatively constant for 70 ka and 400 ka respectively (with the exception of the brief excursion for Kilauea volcano discussed above). On the other hand, old submarine Mauna Loa lavas, between 130 and 200 ka, exhibit fluctuating Zr/Nb ratios that imply a contribution from a Kilauea source component at a time when Mauna Loa was about 20 km closer to the plume axis than it is today. This is the first direct evidence in support of a model of a radially zoned Hawaiian mantle plume. Further sampling of older lavas at greater depths on the flank of the volcano will provide an opportunity to further test these ideas.

TERRANE-TRANSGRESSIVE BATHOLITHS OF WESTERN NORTH AMERICA

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A majority of the Mesozoic batholiths of western North America were emplaced into lithospheric elements (terranes) accreted to and/or migrated along the continental margin. These terranes have been defined laterally by the differential histories recognized in their surface exposures. They range from island arc systems to continental margin arcs to cratonic fragments. Their 3-dimensional characteristics commonly are obscured by complex post-batholithic tectonics, and by sedimentation and volcanism of more recent vintage. Lost Phanerozoic oceanic plates have removed much information vital to setting up successful models. Efforts to infer batholithic source region characteristics and their histories and the timing, nature and evolution of the magma-generating processes are largely incomplete. Interpreting the context of magma-associated mineral deposits often is even less complete. Nevertheless, a broad time-space outline of continent-long magmatic systematics is apparent. Major batholiths formed in Triassic, early to mid-Jurassic, early mid-and late Cretaceous times and continued into the Paleogene during the breakup of Pangaea. The most extensive events took place in the Jurassic and Cretaceous and involved oceanic, peri-cratonic and cratonic source regions. Chemical, isotopic, and mineral assemblage characteristics have helped define many of the magmatic source regions in the more stable of the preserved batholithic fragments. Younger tectonic boundaries can be precisely reconstructed using the disruption of batholithic signature systematics. Older boundaries (sutures) are indicated where high-contrast lithosphere segments had been juxtaposed earlier, but are much less apparent where cratonized blocks have been brought together. Detailed studies by many workers in the Peninsular Ranges-Sonora batholiths as well as in the southern Sierra Nevada and Idaho batholiths illustrate the petrogenetic insights which may be gained as well as the significance of the pre- and post- batholithic tectonics. Bruce Chappell's contributions to these petrogentic insights have been profound.

WATER, RESTITE AND MINERALIZATION

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There is no doubt that "granite" related ore deposits e.g. porphyry tin, porphyry Cu etc are primarily formed from a hydrothermal fluid derived from the magma, although secondary supergene enrichment is probably produced by fluids of meteoric origin. Chemical compositions of granites have previously been discussed as a factor in ore formation but little attention has been directed to H_2O contents. It is suggested that many granite magmas do not expel sufficient H_2O on cooling or decompression to produce an ore deposit.

Estimates of H_2O in granitic magmas vary from about 3 to 5%, but the assumptions on which these figures are based are questionable. Also estimates appear to be based on the assumption that magmas are complete melts: if there is 3% H_2O in a magma containing 50% anhydrous crystals then there must be 6% H_2O in the melt phase. It is suggested that an estimate of 3 wt % H_2O in the sort of granite that gives rise to a porphyry copper deposit is about right. Such an estimate is based on the pressure at which the solubility of H_2O is exceeded in the melt, and when the yield strength of the overlying rocks is just exceeded as a result of the pressure increase when H_2O is released. These are high temperature magmas considered to result from fractional crystallization of a more mafic magma although extensive fractional crystallization involving the feldspars is limited.

It is unlikely that granite magmas produced by different processes such as the low temperature I-type and S-type granites will have similar H_2O contents. These are considered to result from partial melting in which the H_2O content of the melt phase is produced during melt-forming reactions. A simplified melt reaction to produce an S-type magma is:

biotite + quartz + feldspars = OH-bearing melt + orthopyroxene + cordierite

The orthopyroxene and cordierite are restite phases that are produced by the melt reaction. They may occur as perfect crystals because they have grown in the presence of a melt phase. If the melt phase is removed from the restite it will eventually exsolve a fluid phase perhaps as much as 4 wt % on cooling or decompression, but if restite is retained in the magmas crystallization will involve back reaction ie the reversal of the melt-forming reaction and consequently there is no H_2O available for the formation of a hydrothermal solution. S-type magmas (melt + restite) rather than being "wet" may contain less H_2O than many I-types.

Because of the water budget, magmas rich in restite will not produce an ore deposit unless the temperature is high enough for it to fractionate by removal of restite followed by fractional crystallization to increase the H_2O content.

CRUSTAL EVOLUTION IN SOUTHEASTERN AUSTRALIA: A ZIRCON VIEWPOINT

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The Lachlan Fold Belt (LFB) is just part of a broad early Palaeozoic mobile zone that extended along the eastern Gondwana margin at least from the present Trans-Antarctic Mountains about 4000 km to north Queensland. It consists mainly of Ordovician turbidite intruded by Ordovician to Carboniferous granites. Some basic questions to be answered are 1) what is the protosource of the turbidites, 2) are they underlain by older turbidites, oceanic crust, or in part by Precambrian continental crust, and 3) what are the source rocks for the granites?

The LFB S-type granites contain large amounts of inherited zircon, but the I-types have little or none. The inherited zircon can be dated by U-Pb, but have those ages have been affected by the processes of partial melting and magma genesis? At Cooma, an ultrametamorphic S-type granite is preserved at the centre of a regional, low pressure metamorphic aureole within Ordovician turbidite. Detrital zircons from a low grade turbidite remote from the granite cluster in age between 460 and 600 Ma, 1000 and 1200 Ma, and at ~1.8 Ga, ~2.2 Ga and ~2.7 Ga. The granite inherited zircon age groupings are almost identical. Igneous and metamorphic zircon overgrowths and monazite give ~430 Ma, recording simultaneous metamorphism and magma genesis. The inherited zircon preserves an accurate, unbiased record of the ages of the zircons in the granite's sedimentary source rock. Other turbidites, and large, intrusive, S-type granite bodies nearby yield very similar results. In general, the more mafic the granite, the smaller the relative proportion of new zircon growth.

Inherited zircon is much less abundant in the Bega Batholith I-types, but the age groups are the same as in the turbidites and S-types. East to west, across the granite suites, both the abundance of inherited zircon and its mean age increase. This does not simply reflect the progressive evolution of a single magma system; the major element compositions of the different granite suites are similar, and individual suites are time transgressive. There are probably two main sources for the inherited zircon, one contributing just the 500-600 Ma component, the other contributing all components. The granite compositions preclude major host rock contamination during emplacement, so both inherited components most likely come from the granites' source. That is probably mainly 500-600 Ma igneous rock, plus a small sediment component which increases towards the continent. Inherited zircon in the I-type granites' mafic enclaves supports this suggestion. Independent of the range of inheritance ages in the host granite, the inheritance in the enclaves is mainly 500-600 Ma old. Assuming the enclaves to be refractory residues from the igneous source rock, then that rock is dominantly 500-600 Ma old.

The exposed Ordovician turbidites are too chemically mature to be the source of the batholithic S-types; they could be the source of the Cooma granite. Is their zircon signature distinctive? Exploration of detrital zircon ages in Ordovician sediments across the LFB shows that the signature varies very little either regionally or with sediment age. The same components recur, the only differences being small changes in their relative abundances. The same is true of Ordovician sandstone in the Amadeus Basin, and others have traced the signature as far as the Ordovician sediments of New Zealand and, more recently, Antarctica and South Africa. The Ordovician turbidites are part of a large volume of sediment that is very uniform in its protosource over its entire range and is therefore almost certainly not of local origin. Two samples of basal Ordovician turbidite are strongly depleted in the 500-600 Ma component, one Cambrian turbidite from western NSW resembles the Ordovician but lacks zircon younger than ~600 Ma, and a Cambrian sandstone from the Amadeus Basin contains no 500-600 Ma zircon at all. Possibly the characteristic eastern Gondwana zircon age signature was introduced to the area by the Ordovician turbidites. If so, this would limit the source of the S-type granites to being an immature portion of the Ordovician pile. This is consistent with the youngest inherited zircons in some S-type granites and enclaves being ~480 Ma old, implying (if those zircons are not isotopically disturbed) that the source sediments are no older than early Ordovician. There is no compelling evidence that the source (as distinct from the zircons it contains) is Precambrian. Absence of zircon ages reflecting the Australian hinterland make a remote protosource for the sediments, possibly the southern Mozambique Belt, the most likely.

The Palaeozoic granites and sedimentary rocks of eastern Australia share a characteristic zircon age signature that not only demonstrates a petrogenetic link between them, but also is a distinctive fingerprint for eastern Gondwana.

FROM MOLTEN GRANITE TO SOLID ROCK – HOW DOES FRACTIONAL CRYSTALLISATION WORK?

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The great range of granitic bodies of the Lachlan Fold Belt (LFB) provides us with an ideal laboratory for understanding the processes that lead to diversity both within and between granite bodies. At least two large groups of granites of the LFB, the highly fractionated (Rb-enriched) felsic granites and the Boggy Plain Supersuite (BPS), have characteristics that are distinct from most others. These differences have been pointed out in many publications over the last two decades.

The range of compositions within these two specific groups has been ascribed to fractional crystallisation. That is, crystals precipitate from the melt, change the composition of the melt as they crystallise, and hence progressively change the composition of the solid cumulate rocks that are formed. Such solid rock products would comprise a mix of precipitated crystals, and a proportion of trapped melt that is residual from crystallisation. This principle is well-established in mafic and ultramafic intrusives, but has been more difficult to quantify in felsic rocks. Only after combining all the information derived from field relations, petrography, mineral chemistry, lithochemistry and isotopes, for the two distinctive groups, and making comparisons with the other more common granites of the LFB can models be developed that best satisfy all information.

The most compelling evidence that fractional crystallisation is taking place in the felsic granites lies in the behaviour of trace elements accommodated in feldspar. Strong depletions in Ba and Sr are coupled with strong increases in Rb and Cs, while the major element compositions change very little. These characteristics can only be imparted on a felsic liquid by progressive fractional crystallisation of feldspars and quartz close to the Tuttle and Bowen (1958) minimum. The problem is to delineate processes that start with a primary liquid and end with a separation of crystallised phases from a derivative liquid. These processes are taking place at essentially the same temperature and with virtually indistinguishable physical properties of the primary and derivative liquids. We must call upon field relations to provide some evidence of the processes, and the best example is the Lottah Granite in northeastern Tasmania studied by Mackenzie *et al.* (1988). In that pluton a north-central stock is the most primitive. Flat sheets or sill-like bodies spread to the south and southwest for several kilometres, and the rocks become progressively more fractionated away from the central stock. Clearly the fractionation process results from the magma flowing southwards along the sill leaving cumulates behind during its progression. It is that dynamic environment that facilitates the separation of derivative liquid from crystallising phases. For the Lottah Granite, notions of alteration producing the range of chemical compositions of the solid products are now discredited, from a large body of comparative data on similar rocks elsewhere, and from experimental data.

In the BPS, the fractional crystallisation that produced the great range of compositions shown by the group can be ascribed to different dynamical mechanisms to the felsic granites. However before discussing these, it should be pointed out that there are marked differences between mafic rocks of this group and those of other granite groups in the LFB. These differences are obvious, from a field comparison through to the most detailed mineral and chemical investigations. Mafic rocks of the BPS consist of high temperature cumulate crystals with crystallised trapped interstitial derivative melt that ranged in volume from as little as 1% to greater than 40% of the total. The absence of enclaves and crystal clots is in great contrast to mafic rocks from other LFB I-type granites, thought to contain abundant restite. These BPS cumulates are complemented by felsic rocks which include both intrusives and extrusives (high temperature rhyolites). This complementarity leads to a compositional gap with only small volumes of rock in the range 65-70% SiO_2. In contrast, that compositional range dominates among the restite-bearing I-type granites. There is also a strong contrast of BPS extrusives and those thought to contain abundant restite. BPS rhyolites (SiO_2 >70%) contain only sparse high-temperature (1000°C) phenocrysts (plagioclase, pyroxenes, magnetite and ilmenite), while the restite-rich dacites (I- and S-type, SiO_2 <70%) contain abundant phenocrysts (up to 60%) of minerals equilibrated at lower temperatures (800-900°C).

Density differences between the primary and derivative liquids drove the dynamical processes leading to fractional crystallisation of BPS liquids. This was achieved by sidewall crystallisation in some plutons, by the process termed convective fractionation by Sparks *et al.* (1984), or liquid fractionation by McBirney and his co-workers in a series of publications in 1985 and 1997. In the BPS magma chambers, sidewall precipitation of high-temperature cumulate phases produced a derivative liquid with lower density than the primary liquid.

This low density liquid escaped up the walls of the crystallising front. Initially only small amounts of the derivative liquid mixed back into the primary liquid in the core of the chamber, since the derivative liquid was hot, with low viscosity. Derivative liquid accumulated at the top of the chamber with a sharp interface between it and the primary liquid. Some derivative liquid back-mixed into the primary liquid, changing its composition progressively. As inwards solidification proceeded, a greater proportion of the derivative liquid, with progressively higher viscosity (lower temperature and more felsic), back-mixed, until eventually all the derivative liquid was captured into the main chamber. Final solidification proceeded in a closed system. Examples of the processes are found in the Yeoval Batholith where it can be demonstrated, in excellent exposures, that a zoned diorite unit is overlain by a felsic granite cap derived from the same primary melt as the diorite (James, 1997).

The ability of BPS melts to undergo convective fractionation producing complementary dioritic cumulates and felsic derivative liquids is largely related to the relative high proportion of minimum-melt fraction present in the primary melt, which is, in turn, related to the rather potassic character of the liquid in this case. During sidewall crystallisation of high temperature minerals, a relatively large volume of derivative liquid will locally form, resulting in an open crystalline structure and providing an easy escape for the liquid. Taking a tonalitic primary liquid at similar temperature (>1000°C), sidewall crystallisation of high temperature minerals will result in a high proportion of the melt solidifying. The volume of derivative liquid formed is much smaller than with potassic primary liquids. The crystalline structure will be more tightly packed and the derivative liquid will be trapped. No fractional crystallisation will take place. The magma chamber will progressively solidify with little change in composition being possible. A homogeneous body will result. Such bodies are common in the large tonalitic continental margin batholiths of the world.

REFERENCES

Baker, B H, and McBirney, A H, 1985. Liquid Fractionation: Part 3: Geochemistry of zoned magmas and the compositional effects of liquid fractionation. *Journal of Volcanology and Geothermal Research* **24**, 55-81.

James, M, 1997. The geology of the Gullengambel area, central New South Wales. *BSc (Hons) thesis, Australian National University.* 73pp.

Maaloe, S, and McBirney, A R, 1997. Liquid fractionation. Part 4: Scale models for liquid fractionation of calc-alkaline magmas. *Journal of Volcanology and Geothermal Research* **76**, 111-125.

Mackenzie, D E, Black, L P, and Sun, S-S, 1988. Origin of alkali-feldspar granites: An example from the Poimena Granite, northeastern Tasmania, Australia. *Geochimica et Cosmochimica Acta* **52**, 2507-2524.

McBirney, A R, Baker, B H, and Nilson, R H, 1985. Liquid Fractionation: Part 1: Basic principles and experimental simulations. *Journal of Volcanology and Geothermal Research* **24**, 1-24.

Nilson, R H, McBirney, A R, and Baker, B H, 1985. Liquid Fractionation: Part 2: Fluid dynamics and quantitative implications for magma systems. *Journal of Volcanology and Geothermal Research* **24**, 25-54.

Sparks, R S J, Huppert, H E, and Turner, J S, 1984. The fluid dynamics of evolving magma chambers. *Philosophical Transactions of the Royal Society of London* **A310**, 511-534.

Tuttle, O F, and Bowen, N L, 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KalSi_3O_8$-SiO_2-H_2O. *Memoir of the Geological Society of America* **74**, 153pp.

AUSTRALIAN PROTEROZOIC GRANITES - CHARACTERISTICS, SOURCES AND POSSIBLE MECHANISMS FOR DERIVATION AND EMPLACEMENT.

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Granites are a prominent component of almost every Australian Proterozoic orogenic domain. Exposed outcrops of granites and their comagmatic volcanics cover at least 145 000 km^2, and based on gravity and aeromagnetic data, the subsurface extents of granite plutons are likely to be at least 3 times greater. As part of a collaborative project between AGSO and the State and Territory Geological Surveys, and using techniques developed by Bruce Chappell and his coworkers in the Lachlan Fold Belt, some 10 000 chemical analyses were compiled of Proterozoic granites and felsic volcanics, as well as information on their age, mineralogy, host rocks, and associated mineralisation. Using this database and the 'suite' concept (Chappell, 1984), it is possible to identify 9 major types, most of which have analogues in lower Palaeozoic granite suites of the Lachlan Fold Belt.

Most Australian Proterozoic felsic melts were emplaced between 1880 to 1500 Ma, with minor episodes occurring between 1200 to 1050 Ma and at 600-700 Ma. I-type granites predominate. S-types are a minor component and comprise <3 % of the total area of granite exposed. Although I-type granites show distinct compositional changes with time, there are 3 characteristics common to most suites:

1) The majority are I-(granodioritic) type in character with a SiO_2 range of 60 to 77 wt % and there are no significant suites of I-(tonalitic) type or M-types as defined by Chappell and Stevens (1988).
2) Most Australian Proterozoic granites have high K_2O/Na_2O which manifests itself as ubiquitous K-feldspar phenocrysts commonly up to 4 cm in diameter. This high ratio is unique in Australian granites: Archaean granites generally are higher in Na_2O contents, whilst Palaeozoic granites have lower K_2O values.
3) Proterozoic mantle normalised trace element patterns are characteristically Sr-depleted, Y-undepleted and imply derivation from source regions in which plagioclase was stable. This also infers that the granites were derived from depths of <35 km and required geothermal gradients of >30°km^{-1}. These high gradients are compatible with the High Temperature Low Pressure (HTLP) metamorphism that is endemic to Australian Proterozoic terrains. The dominance of Sr-depleted types is also in common with lower Palaeozoic granites of the Lachlan Fold Belt. Sr-undepleted, Y-depleted granites, implying a garnet residual source, comprise <4.0% of Australian Proterozoic granites. This contrasts granites from subduction environments from mid Palaeozoic to recent times which have a far greater abundance of Sr-undepleted, Y-depleted compositions. Australian Archaean granites contain roughly 50% of each type (D.C. Champion, *pers. comm*, 1998).

Within the period 1880 to 1500 Ma Wyborn *et al.* (1997) have shown the dominant Sr-depleted, Y-undepleted I-(granodioritic) types can be further divided into three groups which show a time progression in geochemistry. The oldest group (Group 1) at 1870-1850 Ma (~ 31%), consists of restite-rich granite suites which are characterised by phenocryst-rich volcanics. On Harker variation diagrams the volcanics and granites are chemically indistinguishable, and with increasing SiO_2 most major and trace elements show a linear pattern. Group 2, emplaced at 1840-1800 Ma (~ 30%), is a low-Ca type that shows evidence of magmatic fractionation. There is increasing heterogeneity between individual plutons and leucogranites can clearly be identified. On Harker variation diagrams major and trace element patterns increase exponentially for Rb, U, and Rb/Sr with increasing SiO_2. The youngest group, Group 3 (~24%) is the most enriched in incompatible elements and comprises three subgroups: Subgroup 3_1, dated at around 1800-1780 Ma, has very high values of Zr, Nb and Y; Subgroup 3_2, usually emplaced between 1760 and 1650 Ma, is enriched in F and has variable amounts of Y, Zr, and Nb; and Subgroup 3_3, emplaced from 1640 to 1500 Ma, is more oxidised with a wide range in SiO_2 values and higher CaO and Na_2O contents. This group also has the lowest values of Y, Zr and Nb in Group 3.

Based on the argument that 'Granites are images of their source rocks' (Chappell, 1979) the chemical parameters above constrain source characteristics. The I-(granodioritic) character argues against a direct mantle derivation, and implies an I-(tonalitic) source (Chappell and Stephens, 1988). As the exposed Australian Archaean Crust is strongly bimodal, Proterozoic granites are unlikely to be sourced from Archaean crust as it is either too felsic or too mafic to form the vast quantities of Proterozoic I-(granodioritic) types. Age constraints on the source region are provided by Sm-Nd model ages which range from 2.0 to 2.6 Ma and it has been argued that the sources were underplated, evidence for which is seen in seismic refraction data, which also indicate a plagioclase bearing lower crust (Goncharov *et al.*, 1998) as is required by the mantle-normalised trace element patterns of the granites. The high K_2O contents also require the presence of

K-rich minerals such as K-feldspar, biotite and amphibole in the source region. A simple explanation for the geochemical evolution from Groups 1 to 3 is that as the temperature in the source region increases, the magma production is dominated initially by minium melting of quartz, K-feldspar, albite and some biotite, with calcic plagioclase, amphibole and some biotite being restite phases (*ie,* restite-rich Group 1 granites). As the temperature increases in the source region, melting is initially dominated by biotite breakdown and is then followed by amphibole breakdown as source temperatures reach >1000°C, progressively producing Group 2 then Group 3 granites. In reality there is a continuum between the three Groups which simply reflects increasing temperature in the source region.

However, the inferred increase in lower crustal temperatures between 1880 to 1500 Ma based on the granite data clashes strongly with evidence from the mafic igneous rocks which infer a temperature decrease over the same period, with high Mg-tholeiites dominating before ~1850 Ma and continental tholeiites after ~1850 Ma (with the exception of high Fe-tholeiites at Broken Hill and Mount Isa at ~1690 to 1670 Ma). Most granite suites, particularly in the 1840-1880 Ma range, do show some evidence of coeval mafic intrusions, but these are never comagmatic: nor are they present in sufficient quantities to be the 'heat engine' for generating the required massive crustal melting. Further, recent modelling suggests that temperatures generated by emplacement of mafic intrusions are not likely to reach the high temperatures required for the Group 3_3 granites (1000°C) and that the time taken to generate sufficient crustal melting could actually be >30 Ma (Wyborn *et al.*, 1997). In reality, the tectonic setting in terrains where many of these granites are emplaced are actually characterised by thermal subsidence phases, inferring that the mantle lithosphere is cooling and thickening (*e.g.*, Sandiford *et al*, in press).

Several researchers (*e.g.*, Chamberlain and Sonder, 1990; Sandiford and Hand, 1998; Hobbs *et al.* 1998) have investigated the consequences of high contents of heat producing elements (K, Th and U) within the crust to generate abnormally high geothermal gradients, and ultimately HTLP metamorphism and anatexis. Their work is highly relevant given that Australian Proterozoic granites are more enriched in K, Th, U than at almost any other time with the exception of some late Archaean granites. Independent validation of how high these high K, Th and U values are comes from present day heat flow measurements in the Australian Proterozoic which average 85 mWm^{-2} with values locally in excess of 100 mWm^{-2} (Sandiford and Hand, 1998 based on Cull, 1982). As modelled by Sandiford *et al.* (in press) and Hobbs *et al.*(1998), the end result of these high heat values are high mid-crustal temperatures that do not necessarily cause melting within the lower crust, but that they are capable of it, and perhaps even able to cause minor mantle melting at shallow levels.

What is clear is that modelling by these researchers show that it is possible to generate high temperatures at relatively low pressures without the need for 'active' mantle-driven processes *e.g.*, mantle plumes, mantle underplating or subduction. The conditions for melting come from within the crust, and as each successive granite event in the Proterozoic becomes more enriched in the heat producing elements it may help to explain why the temperatures of formation of the granites are increasing with time, whilst the mantle is cooling - in fact it is paradoxically the mantle cooling that is indirectly causing the crustal melting as the more radiogenic heat sources are progressively buried to deeper levels within the crust by the addition of sediments on top of the crust during thermal subsidence. The efficiency of the heating process is in part controlled by the absolute contents of radiogenic elements in the felsic igneous rocks and in sediments derived from them. The thermal conductivity of the 'burying' sediments also plays an important role in determining the temperatures that are ultimately reached in the crust. It is significant that those Proterozoic terrains containing sequences dominated by quartz sandstones do not have the younger, high temperature granites of Subgroup 3_3. Given the correct conditions, it is possible to generate widespread granitic melting events, instead of linear belts of granite that are commonly associated with subduction or extensional environments. In the Proterozoic many granite suites are large 'amorphous blobs'.

Having created the melts without invoking subduction or mantle plumes, a mechanism is probably still required to allow the melts to intrude into the upper crust. The shape of the apparent polar wander path (APWP) between 1800 to 1500 Ma, confirms that the Australian plate was reasonably mobile at the time of major felsic magma generation. Magma emplacement was also coincident in time with inflection points on the APWP. These inflection points are recognised as significant *interplate* tectonic events with associated *intraplate* effects that cause major episodic migration of basinal fluids. Similar intraplate tectonic responses distal to plate boundary tectonic effects may have also allowed granitic melts to migrate into the upper crust (Wyborn *et al.*, 1998)

It is proposed that crustal heating as a result of high K, Th and U contents within the crust, was possibly responsible for the generation of Sr-depleted, I-(granodioritic) type magmas which dominate the Australian crust from the late Archaean to the Siluro-Devonian. However, similar Sr-depleted I-(granodioritic) types from each major era are distinct in composition, with the radiogenic and incompatible elements decreasing in abundance in each type with time. As the I-(granodioritic) types are ultimately derived from distinct major underplating events, then each successive event must be of a different composition, which is possibly controlled by mantle characteristics changing with time in response to a cooling earth. As the abundance of radiogenic elements clearly decreases with time in I-(granodioritic) types after an initial late Archaean peak, then the ability for radiogenic crustal heating processes to generate significant magma volumes would also diminish with time. This is reflected in the decrease in dominance of Sr-depleted, I-(granodioritic) types after the lower Palaeozoic. Subduction-related processes then appear to become a major granite-generating mechanism resulting in the greater prominence of I-(tonalitic) types (*ie.* Cordilleran granites) in Australia from the mid Palaeozoic onwards.

REFERENCES

Chamberlain, C P, and Sonder, L J, 1990. Heat-producing elements and the thermal and baric patterns of metamorphic belts. Science **250**, 763-769.

Chappell, B W, 1979. Granites as images of their source rocks. *Geological Society of America, Abstracts with Programs* **11**, 400.

Chappell, B W, 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *Philosophical Transactions of the Royal Society of London, Series A* **310**, 693-707

Chappell, B W, and Stephens, W E, 1988. Origin of infracrustal (I-type) granite magmas. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **79**, 71-86.

Cull, J, 1982. An appraisal of heat Australian heat-flow data. *BMR Journal of Australian Geology and Geophysics* **7**, 11-21.

Goncharov, A, Drummond, B J, Tripolsky, A, and Wyborn, L A I, 1998. Average composition of the crust in the Australian, Fennoscandian, and Ukrainian shields from refraction seismic studies and petrophysical modelling. *AGSO Research Newsletter* **28**, 20-28.

Hobbs, B E, Ord, A, and Walshe, J L, 1998. The concept of coupled geodynamic modelling with special reference to the Yilgarn. In: Abstracts for 'Geodynamics and gold exploration in the Yilgarn', *Australian Geodynamics Cooperative Research Centre, Nedlands*, 36-39.

Sandiford, M, and Hand, M, 1998. Australian Proterozoic high-temperature, low-pressure metamorphism in the conductive limit. *In:* Treloar, P.J., and O'Brien, P.J., (eds), *What drives metamorphism and Metamorphic reactions?* Geological Society of London, Special Publications, 138, 109-120.

Sandiford, M, Hand, M, and McLaren, S, in press. High Geothermal Gradient metamorphism during thermal subsidence. *Earth and Planetary Science Letters.*

Wyborn, L A I, Ord, A, Hobbs, B, and Idnurm, I, 1997. Episodic crustal magmatism in the Proterozoic of Northern Australia - a continuum crustal heating model for magma generation. *Australian Geological Survey Organisation, Record* **1997/44**, 131-134.

Wyborn, L A I, Idnurm, M, Budd, A R, Bastrakova, I V, Hazell, M S, and Edgecombe, S M, 1998. What do ~10 000 whole rock geochemical analyses tell us about Australian Proterozoic Intraplate Igneous Activity. *Geological Society of Australia, Abstracts* **49**, 484.

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